TEXAS A&M AGRILIFE RESEARCH & EXTENSION

COTTON ENTOMOLOGY RESEARCH REPORT 2019

TECHNICAL REPORT 20-4

TEXAS A&M AGRILIFE RESEARCH, PATRICK J. STOVER, DIRECTOR
THE TEXAS A&M UNIVERSITY SYSTEM, COLLEGE STATION, TEXAS

COTTON ENTOMOLOGY PROGRAM

RESEARCH ACTIVITY ANNUAL REPORT

2019

SUBMITTED TO:

PLAINS COTTON IMPROVEMENT COMMITTEE
PLAINS COTTON GROWERS, INC.

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Introduction

Plains Cotton Growers, Inc. (PCG) has been a strong supporter of cotton insect research and extension activities in west Texas for many years. Most notably, PCG was instrumental in securing state funds for the Boll Weevil Research Facility at the Lubbock Center, and provided both financial and political support to conduct boll weevil biology and ecology research even before the boll weevil became a significant economic pest of the High Plains region. After the initial entry of the boll weevil into the eastern edge of the High Plains, PCG promoted and along with USDA-APHIS administered the boll weevil diapause suppression program involving a team effort that continued to include Texas A&M University System agencies. PCG also supported Texas Cooperative Extension (now Texas A&M AgriLife Extension Service) efforts to annually evaluate the diapause suppression program, conduct applied research trials to develop boll weevil management practices that would enhance the diapause suppression program's efforts and in the 1990s supported an annual survey of High Plains overwintering sites and grid trapping of cotton across the High Plains area. Under the strong and cooperative leadership of PCG, the boll weevil eradication program for the High Plains area progressed much more rapidly than anticipated. Now, the successful boll weevil eradication program has eliminated the boll weevil from this region for 16 years. In 2015, all 11 West Texas zones (Southern Rolling Plains, El Paso/Trans Pecos, St. Lawrence, Permian Basin, Rolling Plains Central, Western High Plains, Southern High Plains/Caprock, Northern Rolling Plains, Northern High Plains, Northwest Plains, and Panhandle) have been declared boll weevil eradicated and is managed as a single zone called West Texas Maintenance Area (WTMA). The team effort of PCG, Texas A&M AgriLife Research and AgriLife Extension Service over several decades has resulted in a comprehensive understanding of boll weevil ecology and behavior.

With a successful boll weevil eradication program and increased adoption of the transgenic *Bt* technology (now >70%), the cotton insect research and extension program focus has changed considerably during the last 20 years. Our current research/extension focus is on developing ecologically intensive strategies for cotton pest management, including crop phenology, cultivar, non-crop habitat, irrigation, and fertility management towards reducing insect pest pressure. Our research has demonstrated the need for continuing investigation of basic behavior and life patterns of insects while having a strong field-based applied research to bridge the gap between basic, problem-solving science and producer-friendly management recommendations. We have assembled a strong group of people to work as a team to examine multiple disciplines within the broad theme of Cotton IPM. We invest considerable time and manpower resources in investigating the behavior and ecology of major cotton pests of the High Plains with the goal of developing management thresholds based on cotton production technology and economics, with particular focus on limited water production system. Our Program has successfully leveraged research funds based on the funding provided by PCIC to support our research effort. We are excited about and greatly value our Cotton Entomology research and extension partnerships with multidisciplinary scientists at the Texas A&M AgriLife Research Center, together with area IPM agents in the region, to continue this partnership as we challenge ourselves to deliver the best cotton insect-pest management recommendations to our Texas High Plains producers.

EFFECT OF NITROGEN FERTILITY ON COTTON CROP RESPONSE TO SIMULATED COTTON FLEAHOPPER DAMAGE

M.N. Parajulee, A. Hakeem, D. P. Dhakal, Katie Lewis, and J.P. Bordovsky

Objective: The objective was to evaluate the effect of artificial injury to cotton squares mimicking acute cotton fleahopper damage under variable nitrogen application rates on cotton fiber yield and quality.

Methodology: A high-yielding cotton cultivar, NG3406 B2XF, was planted at a targeted rate of 54,000 seeds/acre on June 4, 2019. The experiment was laid out in a split-plot randomized block design with five nitrogen fertility rate treatments (0, 50, 100, 150, and 200 lb N/acre) applied for 17 years as main plots (16-row plots) and two artificial cotton square injury treatments mimicking acute cotton fleahopper infestation as sub-plots with four replications (total 40 experimental units). Within each of the five main-plot treatments included pre-bloom side-dress applications of N augmentation using a soil applicator injection rig on July 19, 2019. Pre-treatment soil samples (consisting of three 0 to 12 and 12 to 24-inch depth soil cores each) were collected from each of the 20 main-plots on June 26, 2019. Ten leaves per plot were collected three times (5 August, 29 August, and 29 September) for leaf dry weight and nitrogen analysis. Within each main-plot, two 8-ft. sections of uniform cotton were flagged in the middle two rows, each receiving hand removal of 100% cotton squares three weeks into squaring or control (no square removal). Five plants were removed to determine biomass. Treatment plots were harvested for lint yield and fiber analysis.

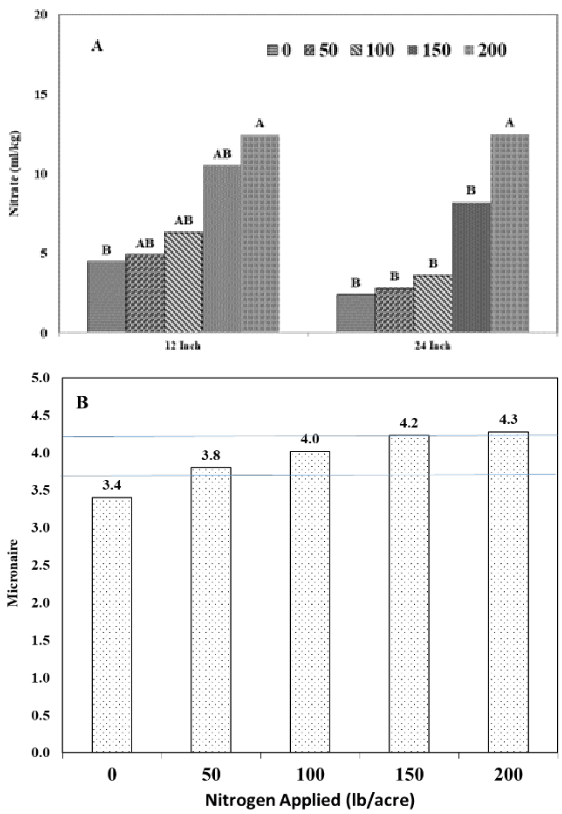

Fig. 1. A) Residual nitrogen recorded from prior year N applied plots at 0-12 and 12-24-inch depths, B) Lint micronaire values affected by variable N augmentation rates.

Results: Significantly higher soil residual nitrogen was recorded from plots that received 200 lb/acre N in preceding 16 years than control plots at 0-12 inch. At 12-24-inch depth, residual N at 200 lb/acre treatment was significantly higher than for remaining N applied treatments (Fig. 1A). The lint quality, measured in terms of micronaire values, was compromised at both zero and 200 lb/A N treatments. While micronaire was barely within the premium range at 150 lb/A, there was a clear trend that the micronaire values increased with N applied rates and the N augmentation >150 lb/A appeared to increase the micronaire value from premium range to a discount territory (Fig. 1B). It is not entirely clear why a low N (zero N augmentation) resulted in lower micronaire. At higher N rates, it is plausible that the carbohydrate supply to maturing bolls increased that resulted in increased micronaire. Simulated square removal did not result in significant change in micronaire values.

TITLE:

Cotton yield response to simulated cotton fleahopper and western tarnished plant bug infestations as influenced by irrigation level and cultivar treatments, Lamesa, TX, 2019.

AUTHORS:

Megha Parajulee – Professor, Faculty Fellow, and Regents Fellow
Abdul Hakeem – Assistant Research Scientist
Dol Dhakal - Research Associate
Wayne Keeling - Professor

MATERIALS AND METHODS:

Plot Size:	4 rows by 300 feet, 3 replications
Planting date:	May 18
Fertilizer in-season:	120-0-0
Cultivars:	PHY 350 W3FE and ST 4946 GLB2

Irrigation:

	Low	High
Preplant	3.1”	3.1”
In Season	5.1”	10.2”
Total	8.2”	13.3”

Herbicides:	Prowl H_2O 3 pt/A – pre-planting Roundup PowerMax 1 qt/A – post planting Roundup PowerMax 1qt/A – post planting
Treatments:	Three treatments included c*ontrol, manual removal of 100% squares three weeks into squaring (July 16) to time cotton fleahopper susceptible stage, and removal of 20% bolls from the top of the plant to simulate Lygus infestation (August 15).*
Boll collection date:	September 11, 2019 to estimate boll penetration pressure
Harvest date:	October 21, 2019 (hand-harvested)

Effect of manual removal of early stage fruits versus control was evaluated on two cotton cultivars, PHY 350 W3FE and ST 4946 GLB2, as influenced by irrigation water level. Experimental design consisted of two square abscission treatments (manual removal of 100% squares to mimic severe cotton fleahopper infestation versus control), two water levels (high versus low) and two cultivars (PHY 350 W3FE versus ST 4946 GLB2), replicated three times and deployed in a randomized complete block design (total 24 plots). In order to mimic a natural early season acute infestation of cotton fleahoppers, a 10-ft section was flagged in each plot and treatments were applied. Square abscission treatments, 1) control (zero square removal) and 2) manual removal off 100% squares, were deployed when cotton was highly vulnerable to fleahopper injury (2-3 weeks into cotton squaring). The test plots were monitored for the occurrence of any other insects, but no such occurrences were observed throughout the growing season. In another study within the same treatment combinations, two 10-ft sections were marked per plot and 20% bolls from the top of cotton plants were removed from *Lygus* injury simulated plots versus no bolls removed from control plots (24 plots).

RESULTS AND DISCUSSION:

Simulation of early-season pest infestations. Combined over two cultivars, significantly higher lint yield was recorded from 'High' water regime (730 lb/acre) compared to that in 'Low' water regime (490 lb/acre) (Fig. 1). No significant difference in lint yield was recorded between fleahopper simulated treatments and control plots regardless of the water regime (Fig. 1). Square removal did not result in significant differences in lint yield between cotton variety PHY 350 W3FE (471 and 683 lb/A) and ST 4946 GLB2 (509 and 779 lb/A) in low and high water, respectively.

Simulation of late-season Lygus-induced boll abortion. Lint yield did not significantly vary between 20% late-season fruit loss via manual pruning and control plots, but the yield penalty of 20% late fruit loss was more prominent in low water treatment than in high water regime (Fig. 2). Also, PHY 350 WFE was more susceptible to late-season fruit loss than ST 4946 GLB2 (Fig. 2). Both in 'low' and 'high' water regimes, significantly higher micronaire was recorded between fleahopper simulated treatments and control plots (Fig. 7), however, no significant differences in micronaire were detected between *Lygus* simulated treatments and control plots both in 'low' and 'high' water regimes (Fig. 8).

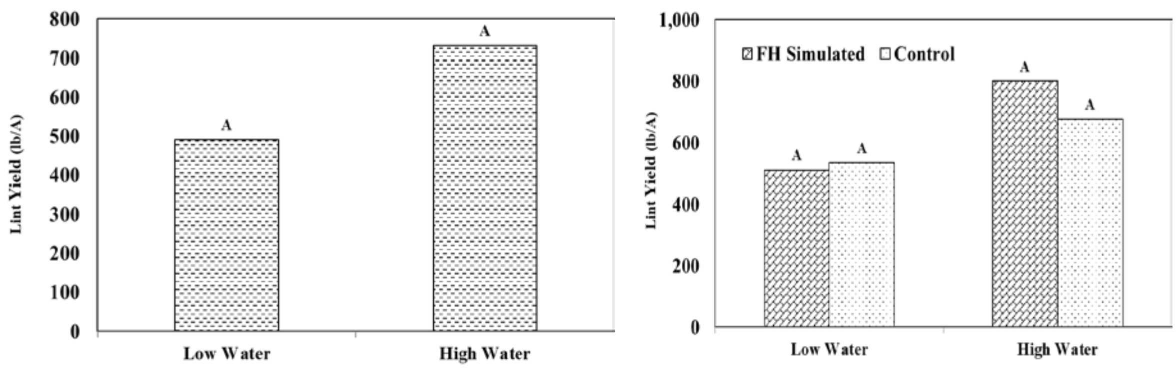

Figure 1. Average lint yield under high and low irrigation regimes (left) and the yield following manual removal of 100% squares prior to first flower versus control plots, Lamesa, Texas, 2019.

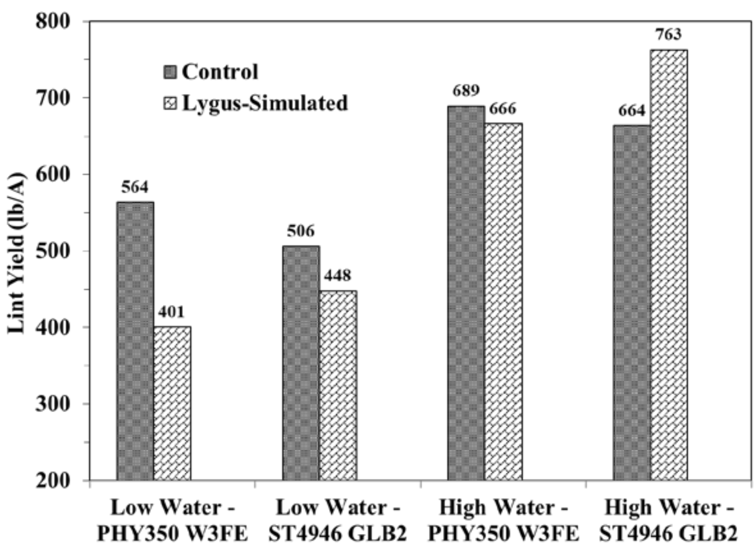

Figure 2. Average lint yield influenced by simulated *Lygus*-induced fruit removal in late season in two cotton varieties under high and low irrigation regimes, Lamesa, Texas, 2019. Average values were not statistically significant due to high variation in data.

Averaged over two cotton cultivars, early-season square removal resulted in increased micronaire values at both irrigation regimes, reaching to the discount range under high water regime (Fig. 3). The effect of late-season simulated *Lygus*-induced fruit removal did not significantly influence the lint micronaire. The increased irrigation water level (high water regime) increased micronaire values in both cotton cultivars, but PHY 350 W3FE had micronaire in the premium range at both irrigation levels while the micronaire values in ST 4946 GLB2 increased to move away from the premium range to the base range (Fig. 4).

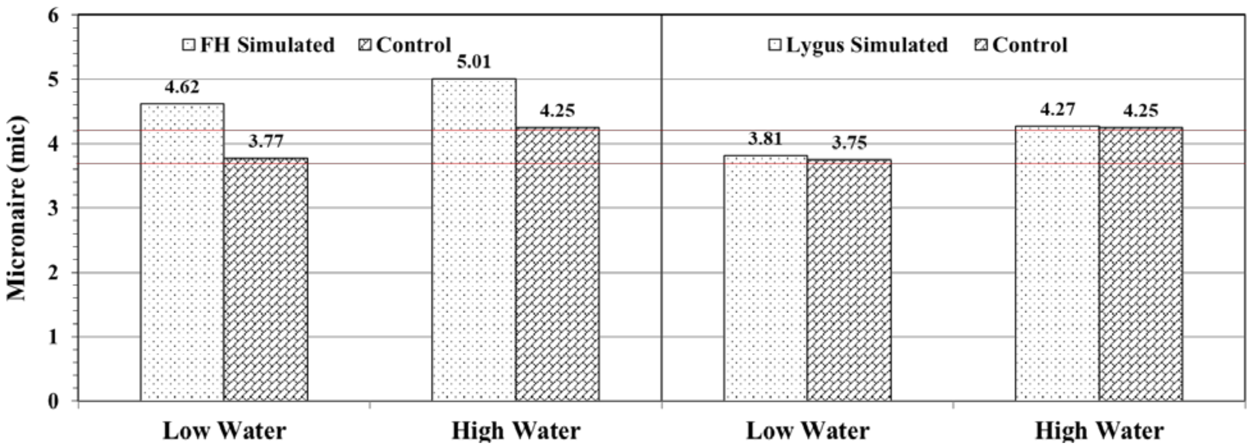

Figure 3. Average micronaire values influenced by early-season simulated cotton fleahopper damage (left) and simulated *Lygus*-induced fruit removal in late season averaged over two cotton cultivars under high and low irrigation regimes, Lamesa, Texas, 2019. The area enclosed by two red lines (3.7-4.2) indicates the microaire values for premium quality cotton lint.

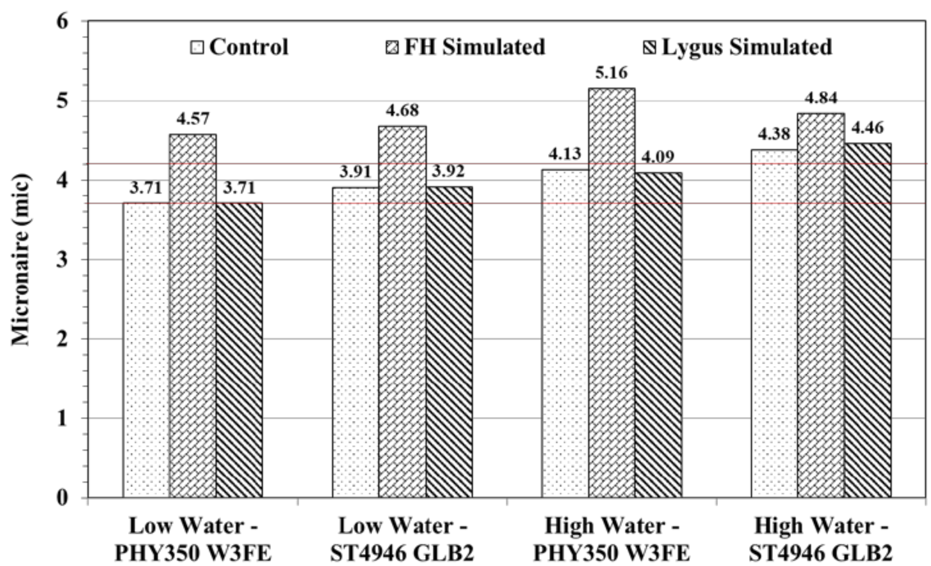

Figure 4. Average micronaire values influenced by early-season simulated cotton fleahopper damage and simulated *Lygus*-induced fruit removal in late season in two cotton cultivars under high and low irrigation regimes, Lamesa, Texas, 2019. The area enclosed by two red lines (3.7-4.2) indicates the micronaire values for premium quality cotton lint.

Cotton Incorporated Core Program

Project Number: 16-354

FINAL REPORT

Effect of *Lygus* on Drought-Stressed Cotton

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Effect of *Lygus* on Drought-Stressed Cotton

Cotton Incorporated Core Program
Project Number: 16-354
PI: Megha N. Parajulee

PROJECT SUMMARY

Western tarnished plant bug, *Lygus hesperus,* is the primary *Lygus* species inhabiting cotton and several other hosts in the Texas High Plains. Our previous studies have documented that several non-cotton hosts including alfalfa, sunflower, corn, grain sorghum, as well as weedy habitats along roadside bar-ditches and turnrows could impact *Lygus* severity in adjacent cotton. Our prior projects, supported by the Cotton Incorporated State Support Program, have generated significant information on the damage potential of adult and immature *Lygus* on maturing cotton bolls. A three-year field study has quantified the boll age (measured in terms of heat units from flowering) that is safe from *Lygus* damage. Boll damage assessment based on heat unit-delineated maturity provided a boll-safe cutoff value of 350 heat units (~2-3 weeks from flowering), although *Lygus* adults and nymphs both cause external lesions on bolls throughout boll development and may give farmers a false impression of *Lygus* damage. A 4-year project (2012-2015) developed economic threshold-based management recommendations for *Lygus* in Texas High Plains cotton for early versus late season *Lygus* infestations.

While the Texas High Plains is fortunate to experience insignificant *Lygus* pressure in cotton during the recent years, the research on *Lygus* feeding behavior as it relates to low-input production systems in the Texas High Plains needs to continue. In particular, the characteristic low annual rainfall and decreasing irrigation water availability in the region has resulted in increased dryland cotton acreage. This project examined the feeding behavior and plant response to *Lygus* injury in relation to drought conditions. Drought-stress treatments included two irrigation levels [full irrigation versus dryland (2016-2017) or supplemental irrigation (2018-2019)], each nested with two cotton cultivars (early maturing versus full-season or nematode tolerant). Each irrigation x cultivar combination received two *Lygus* infestation levels [untreated control versus 2X threshold (high infestation)], each with four replications, resulting in a total of 32 plots.

In 2016, effect of drought-stress on *Lygus*-induced injury was more pronounced in DP 1518 B2XF (38.8% lint loss) compared to that in DP 1044 B2RF (28.2%), suggesting that DP 1518 B2XF may be more susceptible to *Lygus* injury under dryland or water-stressed conditions. Irrigated plots had significantly lower lint loss (<15%) in both cotton cultivars due to *Lygus* feeding compared with that in dryland plots. In 2017, *Lygus*-induced injury reduced lint yield by 41% in dryland versus 29.8% in irrigated cotton. In 2018, *Lygus*-induced injury reduced lint production by 42.7% in supplemental irrigation treatment verses 18% in full irrigation cotton. In 2019, simulated *Lygus* injury rendered no significant lint yield loss in water-deficit condition while a marginal decline in lint yield was observed under full irrigation regime. Our study demonstrated that the impact of *Lygus* injury was more pronounced under dryland and water-deficit growing conditions; likely because late-season lint yield compensations were limited due to reduced water availability limiting future plant growth and fruiting.

Effect of *Lygus* on Drought-Stressed Cotton

INTRODUCTION

Western tarnished plant bug (WTPB), *Lygus hesperus*, is the primary *Lygus* species inhabiting cotton and several other crop and weed hosts in the Texas High Plains region. Previous research indicates that WTPB is a pest of late-season cotton in the Texas High Plains. Regional survey work suggests that WTPB generally do not move from roadside weed habitats to cotton until late during the season as bolls mature, at which time roadside weeds decrease in prevalence or suitability. However, WTPB can be a significant economic pest of squaring and/or flowering cotton if they are forced to move into cotton in the absence of roadside weed habitats due to drought.

Due to utilization of underground water in excess of its recharge capacity and characteristic low rainfall in this semi-arid region, the Texas Southern High Plains has been facing some significant drought conditions in recent years. This has resulted in many of our cotton acreages going to dryland or limited-irrigation production. The shift in cotton production system from 60:40% irrigated:dryland to 40:60% in just the last 10-15 years has altered our input resources, cultivars, and management practices. It is generally expected that the drought-stressed plants would be significantly more impacted by insect injury than fully irrigated crops, but the drought-stressed plants would also likely have lower fruit load thresholds. However, a plant's ability to compensate for *Lygus*-induced crop damage may be greatly impacted by the drought-stress conditions, with possibly a low infestation rendering proportionately higher damage to the crop.

Cotton plant growth is sensitive to numerous environmental and management input factors, particularly irrigation and nitrogen fertility. Cotton growth responses to various input factors are well-documented and growth models have been developed. However, the specific cotton plant responses to *Lygus* injury under a range of irrigation regimes remain uninvestigated. Plant bugs have a general inclination to attack the stressed plants and cause significant damage. The greater damage on stressed plants compared to healthy plants is partly due to the inability of plants to physiologically react to the injury. Thus, it is expected that the drought-stressed plants would be more vulnerable to *Lygus* injury than unstressed plants. However, the fruit-load threshold of a cotton plant is also dependent on soil moisture availability, among several other input and management factors. There is no information on how *Lygus* feeding behavior will be impacted under various irrigation regimes and how the plants would respond to varying levels of *Lygus*-induced injury under drought conditions. Similarly, cotton cultivars respond differently to various moisture stress conditions and the interactive effect of *Lygus* injury, phenological attributes of cotton cultivar, and drought conditions are unknown. The overall goal of this study was to characterize the effect of drought conditions on *Lygus* infestation/feeding behavior and plant response to *Lygus* injury.

METHODOLOGY

A four-year study was initiated in 2016 in a multi-factor split-plot randomized block design with four replications (blocks). Drought-stress parameters included two irrigation levels (full irrigation versus dryland) that served as main plot factors, whereas two cotton cultivars (early maturing versus full-season) were used as subplot factors to create an interaction of cultivar maturity and drought-stress situations to mimic the Texas High Plains (THP) scenario during dry summers. The full irrigation water level was created via 100% replenishment of evapotranspiration (ET) requirement for THP, whereas the dryland treatment received no supplemental irrigation. Two cotton cultivars included in the study were DP 1518 B2XF (short-season) and DP 1044 B2RF (full-season) (2016-2017) and DP 1820 B3XF and DP 1823NR B2XF (2018-2019), planted on 25 May 2016, 26 May 2017, 29 May 2018, and 22 May 2019. While both DP 1820 B3XF and DP 1823NR B2XF were early to mid-maturing cultivars, DP 1823NR B2XF offered significant nematode tolerance, offering cultivar differences for comparison. Each irrigation treatment (2) x cotton maturity (cultivar type) treatment (2) received two *Lygus* infestation levels [untreated control, 2X threshold (high infestation) in 2016-2018 and simulated *Lygus* damage in 2019], each with four replications, resulting in a total of 32 plots. In 2017, due to logistic limitations, the study was conducted only on DP 1518 B2XF. In 2019, in addition to simulated *Lygus* damage study, *Lygus* bugs were released on DP 1646 B2XF under dryland and high water (full irrigation) regimes as an adjunct study within the same cotton field with two extreme water treatments.

Lygus density treatments were applied on one 3-ft cotton row section per plot on August 11, 2016, August 18, 2017, August 22, 2018, and August 30, 2019. For insect release plots, a single release of *Lygus* adults (5 adult *Lygus* per plant, resulting in 1 bug per plant after 80% field mortality) was timed to simulate the acute infestation of *Lygus* while cotton was at boll development/maturation stage. Multi-plant (6-7 plants) cages were used to contain the released adults (Fig. 1). The control plots were flagged and sprayed with insecticides. Two weeks after the deployment of insect release treatments, all experimental plots were sprayed with insecticide Orthene® 97 to ensure that the released insects were removed. One to two plants from each treatment were removed and processed for *Lygus* damage assessment. Variables including number of fruits aborted and internal/external damage to developing bolls were measured. The 2019 simulated *Lygus* infestation trial was deployed on 30 August 2019 when plants were at active boll development stage. Twenty percent bolls from the top third of the plants (3 row ft) from each treatment were removed to mimic late-season *Lygus* infestation. On 19 September 2019, 10 quarter-sized bolls were collected from each treatment randomly and the amount of pressure required to puncture the carpel wall was recorded using a penetrometer. Boll size and weight were also measured. Pre-harvest plant mapping was conducted, and crop was hand-harvested on November 5 (2016), November 2 (2017), November 5 (2018), and October 31 (2019) and ginned. Lint samples were sent to Cotton Incorporated for fiber quality analysis.

Figure 1. A and B) Multi-plant cages used for *Lygus* release, C) Examination and data collection from the test site.

RESULTS

2016 Study. As expected, higher numbers of internal warts were observed in bolls collected from *Lygus*-infested plants compared to that in control plots (Fig. 2). *Lygus* appeared to cause greater damage to dryland-grown plants compared to that in full irrigation plots. It is somewhat interesting to note that the dryland plots received greater boll injury while the bolls in dryland plots are expected to possess a tougher carpel wall. It is possible that the water-stressed bolls are more sensitive to *Lygus* feeding injury.

Averaged across the water level and cultivar treatments, total boll density on *Lygus*-infested plants was lower (2.27 bolls per plant) compared to that on uninfested control plants (3.2 bolls per plant) two weeks after *Lygus* infestation, suggesting possible abortion of small bolls due to *Lygus* feeding. Within varieties, DP 1518 B2XF had slightly more (2.8 bolls per plant) bolls compared to DP 1544 B2RF (2.6 bolls per plant), but this difference was not statistically significant.

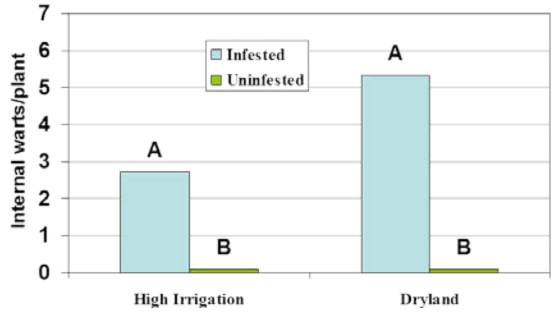

Figure 2. Internal injury warts in developing bolls caused by *Lygus* feeding on plants grown under full irrigation versus dryland, Lubbock TX, 2016.

Averaged across cultivars and irrigation treatments, no significant difference in lint yield was observed between *Lygus*-release treatments and non-release control treatments. However, drought-stress induced a significantly greater impact of *Lygus* injury on cotton lint yield. *Lygus* injury caused 34.83% lint yield loss in dryland cotton compared to only 11.3% loss in irrigated cotton (Fig. 3), suggesting a reduced *Lygus* injury sensitivity on full irrigated cotton compared to that in water-stressed production situation.

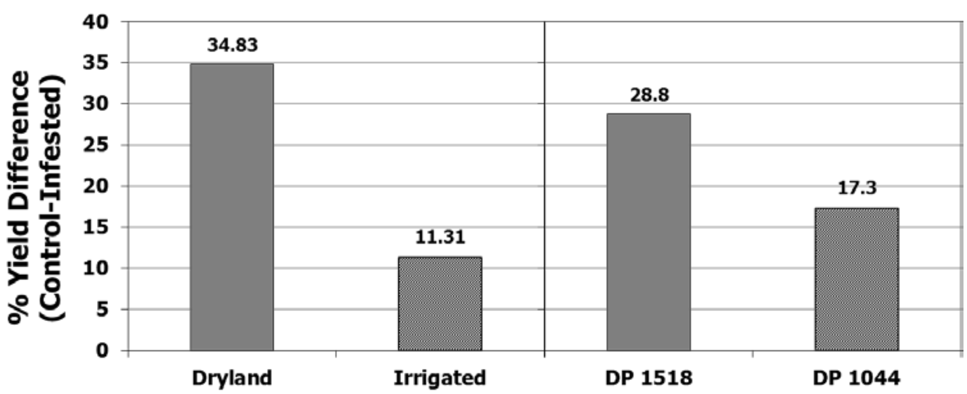

Figure 3. Effect of *Lygus* bug-induced damage on lint yield of cotton under dryland and irrigated production conditions and between the two cultivars, Lubbock, TX, 2016.

Lygus injury sensitivity varied between cultivars. While no significant difference in total lint yield was observed between the two cotton cultivars evaluated, *Lygus*-induced lint yield reduction was significantly greater (28.8%) in DP 1518 B2XF compared to 17.3% in DP 1044 B2RF (Fig. 3).

Effect of drought-stress was more pronounced in DP 1518 B2XF (38.8% lint loss) compared to that in DP 1044 B2RF (28.2%) (Fig. 4), suggesting that DP 1518 B2XF may be more susceptible to *Lygus* injury under dryland or water-stressed conditions. Irrigated plots had significantly lower lint loss in both cotton cultivars due to *Lygus* feeding compared with that in dryland plots (Fig. 4). The 2016 study indicated that DP 1044 B2RF appeared to show lower sensitivity to *Lygus* injury under both dryland and irrigated conditions, but the impact was more pronounced under dryland condition.

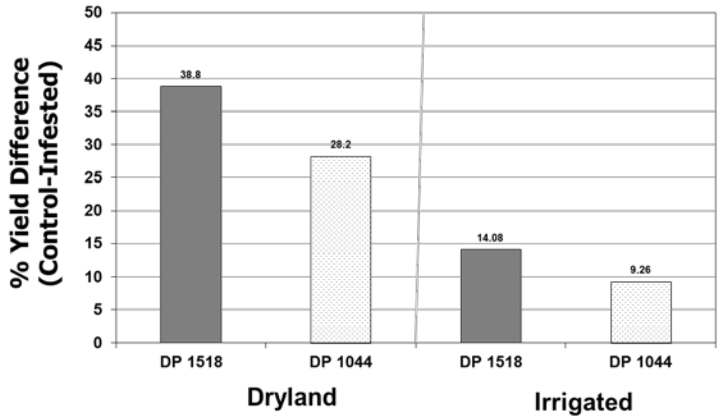

Figure 4. Percentage yield losses due to *Lygus* infestation under dryland versus irrigated production conditions, Lubbock, Texas, 2016.

2017 Study. *Lygus* augmentation exerted significant injury to the maturing bolls in both dryland and irrigated cotton (Fig. 5). There was a slight increase in the number of external lesions, internal boll injury warts, and damaged seeds in irrigated cotton compared to that in dryland cotton, but the trend was similar between the two irrigation treatments. Even though the *Lygus* injury caused a lower amount of visible damage in dryland cotton compared to that in fully irrigated cotton (Fig. 5), drought-stress appeared to render greater boll vulnerability to *Lygus* injury for continuing boll growth, lint development, and fiber quality.

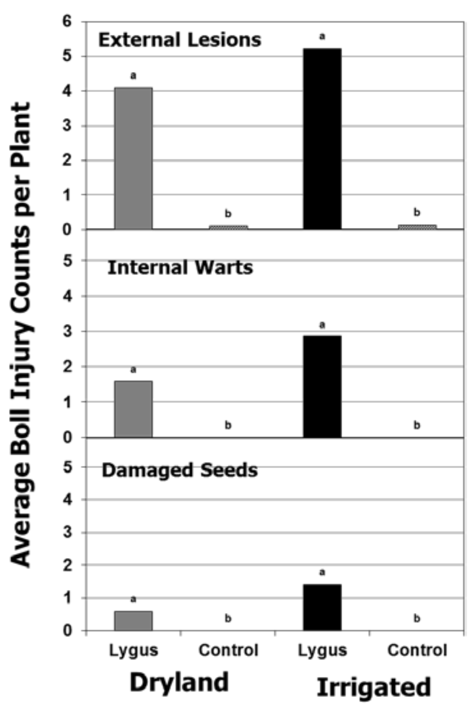

Figure 5. External lesions, internal injury warts, and damaged seeds in developing bolls caused by *Lygus* feeding on plants grown under full irrigation versus dryland, Lubbock TX, 2017.

Lygus augmentation significantly reduced lint yield in both fully irrigated and dryland conditions. As expected, dryland plots produced lower lint yield compared to that in irrigated plots (Fig. 6). Within dryland, un-augmented control plots produced 1,292 lbs of lint per acre compared to 762 lbs per acre when *Lygus* bugs were augmented and injury was inflicted to the maturing crop. Similar relationship was observed under full irrigated crop production system, with 1,974 lbs per acre lint yield in control plots and 1,386 lbs per acre in *Lygus*-augmented plots (Fig. 6). Irrigated plots had significantly lower lint loss (29.8%) due to *Lygus* feeding compared with that in dryland plots (41.0%) (Fig. 7).

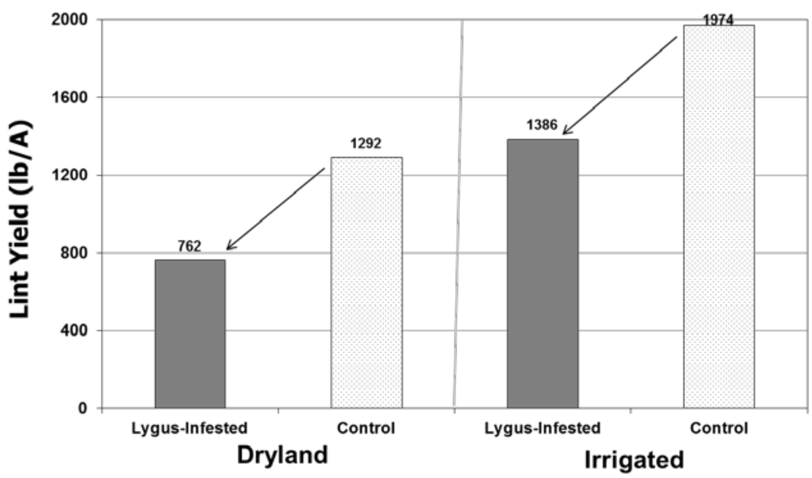

Figure 6. Cotton lint yield losses due to *Lygus* infestation under dryland versus irrigated production conditions, Lubbock, Texas, 2017.

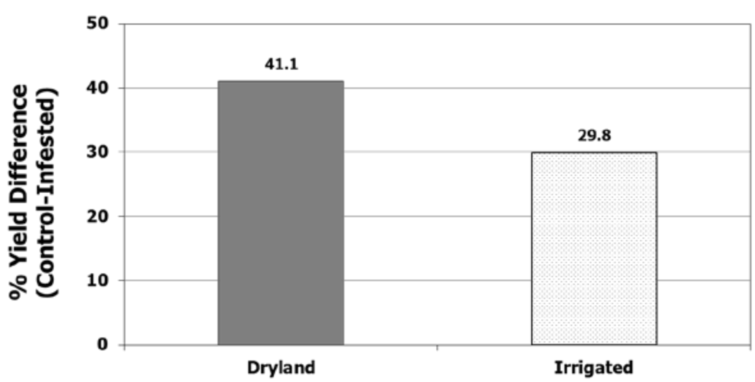

Figure 7. Percent lint yield losses due to *Lygus* infestation under dryland versus irrigated production conditions, Lubbock, Texas, 2017.

2018 Study. In 2018, *Lygus* bugs were released on two varieties (DP 1820 B3XF and DP 1823 NRB2XF) under low (supplemental) and high water (full irrigation) regimes. *Lygus* augmentation exerted significant boll injury in both supplemental and full irrigation treatments. As expected, significant external lesions, internal warts, and seed damages were observed in Lygus-infested plots compared to that in uninfested control plots (Fig. 8). Overall, *Lygus* exerted greater damage to bolls in full irrigation treatments compared to that in cotton with supplemental irrigation.

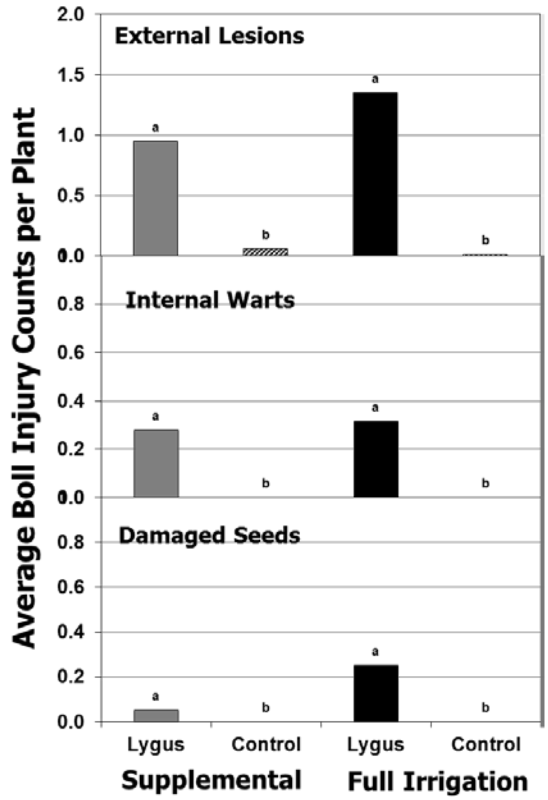

Figure 8. External lesions, internal injury warts, and damaged seeds in developing bolls caused by *Lygus* feeding on plants grown under supplemental versus full irrigation, Lubbock TX, 2018.

Lint yield significantly varied between the two cultivars, with higher lint yield in DP 1823NR B2XF compared with that in DP 1820 B3XF regardless of the irrigation amount (Fig. 9). Also, as expected, full irrigation increased yield significantly in both cultivars compared with supplemental irrigation. However, full irrigation produced significantly higher lint yield compared with that in supplemental irrigation in DP 1823NR B2XF (1,223 lb/acre versus 1,020 lb/acre) while the yield was similar between the two irrigation regimes for DP 1820 B3XF (961 lb/acre versus 950 lb/acre). *Lygus* infestation negatively impacted the lint yield in both cultivars at both irrigation regimes (Fig. 9). Combined over two cultivars, supplemental irrigation resulted in 642 and 985 lbs/acre in *Lygus*-infested and control plots, respectively, whereas the full irrigation increased lint yield to 816 lb/acre and 1,092 lb/acre for *Lygus*-infested and control plots, respectively.

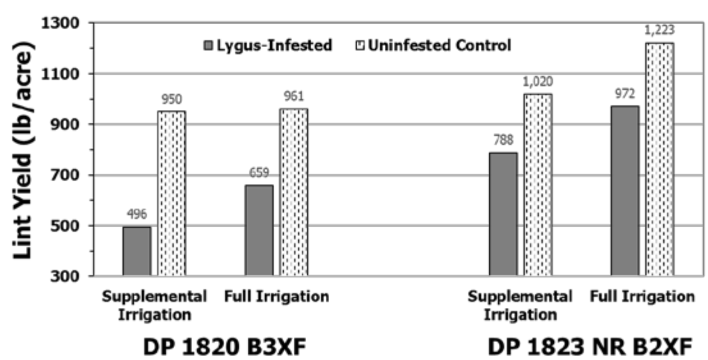

Figure 9. Cotton lint yield losses due to *Lygus* infestation under supplemental versus full irrigation production conditions, Lubbock, Texas, 2018.

The effect of *Lygus* was more pronounced on DP 1820 B3XF compared to that for DP 1823NR B2XF (Fig. 10). The highest yield reduction (48%) was observed in DP 1820 under supplemental irrigation, followed by DP 1820 full irrigation (31%), and lowest reductions were observed in DP 1823 supplemental (23%) and full irrigation (21%) (Fig. 10). As observed in previous years, *Lygus* induced greater lint yield loss under water-deficit conditions compared to that under full irrigation conditions. However, the difference was not significant with DP 1823NR B2XF. It is illustrated that the *Lygus* impact on lint loss that is modulated by the amount of irrigation/water availability is also influenced by the cultivar's potential to tolerate *Lygus* injury.

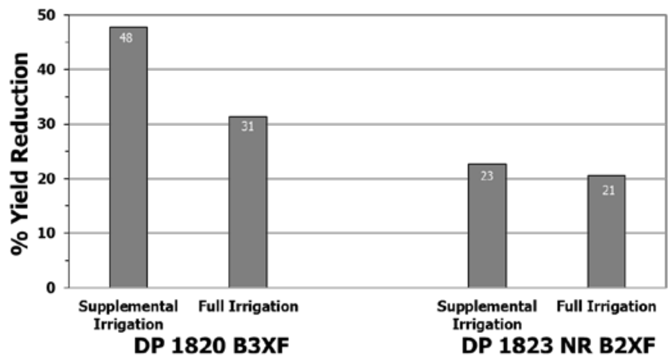

Figure 10. Percent lint yield losses in two cotton cultivars due to *Lygus* infestation under supplemental versus full irrigation production conditions, Lubbock, Texas, 2018.

2019 Study. In 2019, simulated *Lygus* damage was exerted on two cotton cultivars (DP 1820 B3XF and DP 1823NR B2XF) under low (supplemental) and high water (full irrigation) regimes around cut-out. No significant differences in fresh boll weight was observed from cotton varieties DP 1820 B3XF and DP 1823NR B2XF under supplemental and full irrigated plots (Fig. 11). Also, no significant differences in boll pressure was observed in supplemental irrigation plots versus full irrigation plots (Fig. 12).

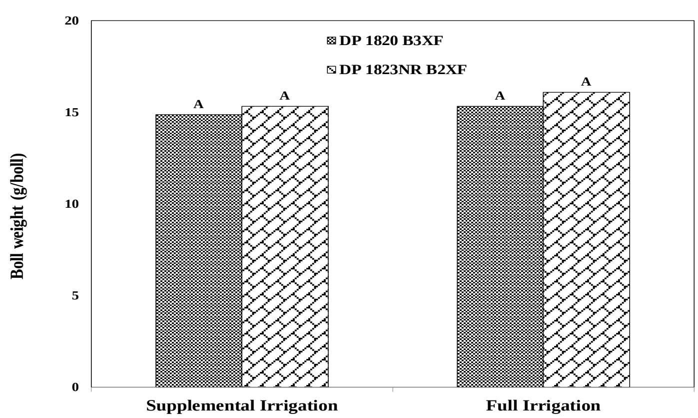

Figure 11. Green boll weight affected by cotton varieties under supplemental irrigation versus full irrigation, Lubbock, TX, 2019.

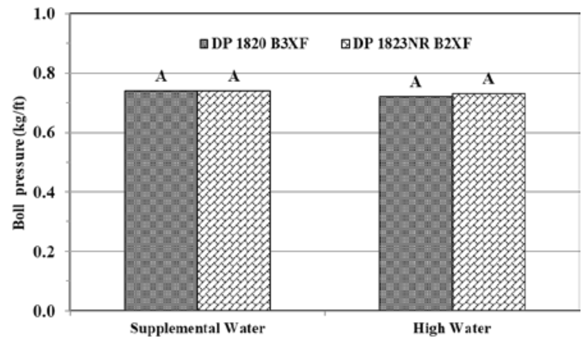

Figure 12. Penetrometer pressure required to puncture boll carpel wall (15 bolls per plot) influenced by supplemental versus full irrigation, Lubbock, TX, 2019.

Boll pressure was significantly lower in dryland plots compared to that in full irrigated plots (Fig. 13). These differences were due to the fact that dryland plants were more matured than plant in full irrigation plots by the time the plants were at cut-out stage. Availability of ample water rendered plants more succulent and the bolls were less hardened compared to that in dryland plots.

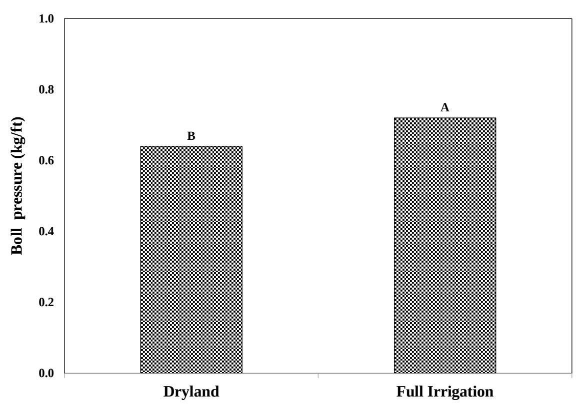

Figure 13. Penetrometer pressure required to puncture boll carpel wall (15 bolls per plot) in cotton cultivar DP 1646 B2XF influenced by dryland versus full irrigation, Lubbock, TX, 2019.

No significant differences in lint yield was observed from simulated *Lygus* damage and control treatments under supplemental irrigation plots, however, significantly higher lint yield was observed from control treatments than simulated *Lygus* damage treatments under full irrigation treatments (Fig. 14). These data are in contrast with the last three years when the Lygus-induced boll damage resulted in significant yield loss at all irrigation water levels. Therefore, it appears that the mechanical removal or thinning of late season bolls do not pose the yield penalty, suggesting that the plants likely reallocate the resources to enhance the growth and maturation of the remaining fruits on the plants.

Cotton cultivars showed varied response to simulated *Lygus* damage. Cultivar DP 1820 B3XF compensated for the manual fruit pruning induced yield loss under supplemental irrigation, whereas the compensation did not occur at full irrigation regime. It is plausible that the plants under full irrigation asymmetrically allocated the resources to vegetative growth after the fruit pruning rather than diverting the available resources to fruit development and maturity. However, DP 1823NR B2XF compensated for the manual pruning of fruits and resulted in similar yields between simulated damage versus untreated control plots at both irrigation regimes (Fig. 15).

In our adjunct study, *Lygus*-induced injury resulted in 45 and 50% yield loss in dryland and full irrigation plots (Fig. 16). Although the cultivar in 2019 *Lygus* augmentation study (DP 1646 B2XF) was different than the ones used in the last three years, 50% yield reduction in full irrigation treatment was unexpected. In previous years, the availability of sufficient irrigation water reduced the potential yield loss due to *Lygus* injury; however, the yield loss was similar between the two extreme water regimes in this trial.

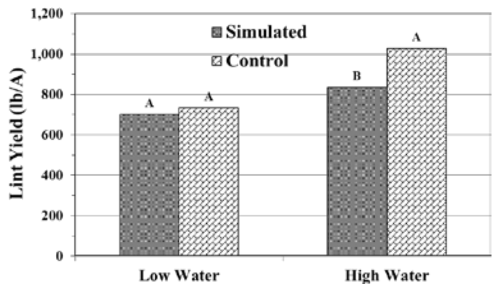

Figure 14. Cotton lint yield losses due to simulated *Lygus* infestations under supplemental versus full irrigation production conditions averaged across two cultivars, Lubbock, Texas, 2019.

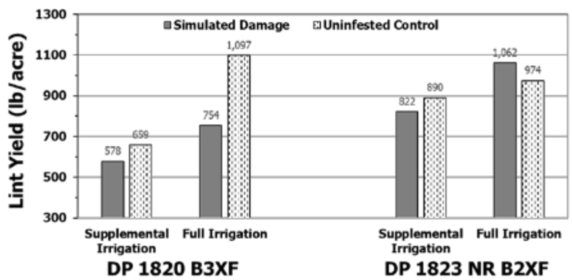

Figure 15. Effect of simulated *Lygus* damage on two cotton cultivars under supplemental versus full irrigation production conditions, Lubbock, Texas, 2019.

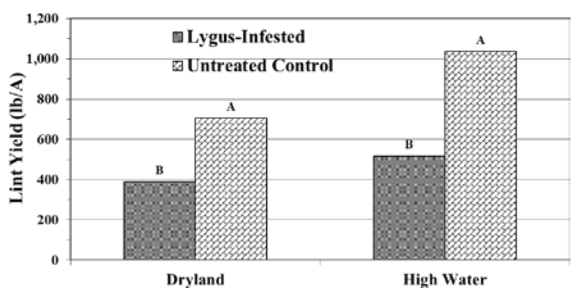

Figure 16. Lint yield losses in cotton cultivar DP 1646 B2XF due to *Lygus* infestations under dryland versus full irrigation production conditions, Lubbock, Texas, 2019.

Acknowledgments

Research funding which facilitated this study came from Cotton Incorporated Core program and Plains Cotton Improvement Program.

Economic Evaluation of Insect-Pest Management in Water-Deficit Cotton Production

Cotton Incorporated - Texas State Support Committee

Project Number: 18-099TX
PI: Megha N. Parajulee
CO-PIs: Abdul Hakeem, Suhas Vyavhare, Katie Lewis, Wayne Keeling, and Donna McCallister

PROJECT SUMMARY

The Texas High Plains (THP) is a semi-arid region with characteristic low rainfall, with production agriculture supported by limited irrigation or rain-fed. As a result, the cropping system in this region is largely low-input and the producer decision-making in economically profitable input use is a challenge. THP has been facing some significant drought conditions in recent years, including the drought of 2011 that claimed much of the Texas production agriculture, reducing total cotton yield that year by 55%. Drought conditions ensued the next 3 years that disproportionately depleted the underground water, significantly shifting the cotton production outlook in THP to even more low-input with dryland acreage reaching to >65%. The shift in cotton production system due to devastating droughts in an already semi-arid region has altered our input resources, cultivars, and management practices. Low cotton market price, increased nitrogen fertilizer price, and reduced water availability have forced farmers to move toward reorganizing available input resources to sustain their production enterprise. Thus, transitioning to the new crop production reality via developing economic data-based input management practices has become our priority to sustain producer profitability.

The objectives of this project were to: 1) quantify the impact of single (thrips or cotton fleahoppers) versus multiple (thrips and cotton fleahoppers sequentially) pest infestations on cotton lint yield and fiber quality under three irrigation water regimes (water-deficit treatments), and 2) develop a dynamic optimization economic model that maximizes the net returns from management of single versus multiple pest infestations under water-deficit crop production conditions. Thus, the scope of this proposed work entails integrating production practices and pest management options under numerous cotton management scenarios (15 total scenarios) and the management options would be developed based on breakeven value and net return of each option for farmers to choose depending on the availability of water resources on their farms.

In 2018 and 2019, thrips and fleahoppers impacting cotton production risks were evaluated with five combinations of single versus sequential infestations under three water-deficit (near-zero deficit or full irrigation, supplemental, and high deficit or dryland) regimes, replicated four times (total 60 plots). Water deficit conditions and insect infestations impacted crop growth profile as well as lint yield. For example, fleahopper infestation resulted in increased apical growth of the plants in water-deficit conditions, whereas sequential infestation of two insect pests increased the plant apical growth in irrigated plots (2018). Lint yield was similar across all five treatment combinations under dryland condition while the sequential infestation of two pests (2018) and cotton fleahopper augmentation (2019) significantly reduced the lint yield compared to untreated control under irrigated condition, indicating the impact of drought conditions on modulating the effect of insect pests as well as the plant's compensatory ability.

Economic Evaluation of Insect-Pest Management in Water-Deficit Cotton Production

INTRODUCTION

The Texas High Plains (THP) is a semi-arid region with characteristic low rainfall (average annual rainfall of 15-18 in.), with production agriculture supported by limited irrigation or rain-fed. As a result, the cropping system in this region is largely low-input and the producer decision-making in economically profitable input use is a challenge. THP has been facing some significant drought conditions in recent years, including the drought of 2011 that claimed much of the Texas production agriculture, reducing total cotton yield that year by 55%. Drought conditions ensued the next 3 years that disproportionately depleted the underground water, significantly shifting the cotton production outlook in THP to even more low-input with dryland acreage reaching to about 70%. The shift in cotton production system due to devastating droughts in an already semi-arid region has altered our input resources, cultivars, and management practices. Low cotton market price, increased nitrogen fertilizer price, and reduced water availability have forced farmers to move toward reorganizing available input resources to sustain their production enterprise. While the drought and heat conditions are unpredictable, the anticipated changes in global climate patterns may exacerbate the water-deficit conditions further in the THP. Thus, transitioning to the new crop production reality via developing economic data-based input management practices has become our priority to sustain producer profitability and for future success of the U.S. cotton industry.

Much has been reported on direct and indirect effects of drought stress on cotton, but the effect of drought stress on cotton insect pest dynamics, feeding potential, and plant’s response to insect injury under drought-stressed conditions are limited. In addition, the paucity of information on integration of pest management decisions and crop production decisions has hindered producers’ ability to predict economic risks of optimizing limiting input resources. Predicting pest populations under different water-deficit crop production scenarios and understanding how these conditions influence those populations to impact crop production risks, are critically important components for implementing pest management strategies as crop cultivars and other input variables continue to change. Reduced water availability, low rainfall, higher pumping cost of limited water, and increased input cost may result in lower yields and correspondingly lower profit margins, warranting for higher water use efficiency in our crop production. Therefore, cotton producers must carefully consider costs of pest management options against potential benefits to overall net profit margin of the crop production enterprise. The objectives of this project are to: 1) Quantify the impact of five combinations of single versus sequential infestations of two major insects (thrips and cotton fleahoppers) on cotton lint yield and fiber quality under two irrigation water regimes (water-deficit treatments – near dryland versus full irrigation), and 2) Develop a dynamic optimization economic model that maximizes the net returns from management of single versus sequential pest infestations under water-deficit crop production conditions. Thus, the goal of this project aims to integrate production practices and pest management options under numerous cotton management scenarios (10 total scenarios) and the management options will be developed based on breakeven value and net return of each option for farmers to choose depending on the availability of water resource on their farms.

METHODOLOGY

A multi-year study was initiated in 2018 on a five-acre subsurface drip irrigation cotton field located at the Lubbock Texas A&M AgriLife Research farm (Lubbock County, TX).

Irrigation water level treatments. Three irrigation water levels (dryland, supplemental irrigation, and full irrigation) simulated three water-deficit production conditions, including high water-deficit (dryland condition), limited water condition, and no water deficit. A high-water treatment maintained >90% evapotranspiration replenishment through subsurface drip irrigation throughout the crop growing season, supplemental irrigation maintained about 40% ET replenishment, and the dryland treatment received pre-planting irrigation to facilitate proper seed germination and no additional irrigation. In 2018, only dryland and full irrigation main plot treatments were available; 2019 and beyond will have three water levels.

Planting and field management. The 2018 study followed the conventional tillage system of cotton cultivation and regionally adopted production practices were followed, including pre-planting application of 80 lb N/acre. Cotton cultivar DP 1646 B2XF (seed with no insecticide or fungicide seed treatment) was planted on 31 May 2018. In 2019, wheat was planted on 14 February 2019 as a cover crop to minimize pre-planting soil erosion and prevent cotton seedlings from sandblasting during May/June. Cotton cultivar DP 1646 B2XF was planted on 14 May 2019 and the wheat was terminated on 20 May 2019 with Roundup WEATHERMAX® (48.8% glyphosate) @ 32 oz./Acre to facilitate thrips movement to emerging cotton seedlings. Other field management activities included the tank-mixed application of herbicide XTENDIMAX® (48.8% dicamba) @ 22 oz./Acre and Roundup WEATHERMAX® (48.8% glyphosate) @ 32 oz./Acre on 17 June, 2019 for weed management, field cultivation on 24 June 2019 for soil aeration and weed management, and fertilizer application (100 lb. N/acre) via side-dressing on 23 July 2019.

Insect infestation treatments. Two key early-season insect-pest species (thrips and cotton fleahoppers) impacting cotton production risks were evaluated with five combinations of single versus sequential infestations (Table 1) under two water-deficit (zero versus high) regimes, replicated four times (total of 40 experimental plots). Targeted insect management options were achieved via artificial infestation of insect pests. Because Texas High Plains cropping conditions rarely warrant more than a single insecticide application to suppress either of the two major insect pest groups (thrips at seedling stage and cotton fleahopper at early squaring stage), our experiment was designed to infest our treatments at the most vulnerable stage of crop for the species infested.

Table 1. Five insect management scenarios evaluated under three irrigation water treatments, Lubbock, Texas, 2018-2019

Treatment #	Insect Infestation Treatment Simulated via Artificial Infestation
1	All insects suppressed (No insect infestation) (sprayed control)
2	Thrips occurring at 1-2 true leaf stage
3	Cotton fleahoppers occurring during the first week of squaring
4	Thrips and cotton fleahoppers infested sequentially
5	No insect management (untreated control)

Insect augmentation: 2018 study

Thrips. Thrips were released to seedling cotton on 19 June 2018 when the crop was at 1-2 true leaf stage. Thrips infested alfalfa terminals were excised from a healthy alfalfa patch and these terminals were laid at the base of young cotton seedlings. Thrips were expected to move onto the cotton seedlings as excised alfalfa sections began to dry. Approximately 6 thrips per seedling were released to two 5 row-ft sections (approximately 12 plants per section) per plot (approximately 140 thrips per thrips-augmented plot). Thrips were released on all 16 thrips-augmentation plots (treatments #2 and #4 x 2 water levels x 4 replications) on the same day. Thrips were released on four additional plots to estimate thrips movement onto the cotton seedling via absolute sampling of seedlings and washing of thrips 3 days post-release. Data showed that the seedlings received an average of 1.2 live thrips per seedling which is the threshold density for 1-2 leaf stage seedling cotton.

Uncharacteristic high daytime temperatures for the next 7 days following the thrips release (103-107 ^{o}F) contributed to low thrips feeding performance and perhaps high thrips mortality after the thrips moved to the seedlings. Consequently, no visible signs of thrips-feeding effect were observed in thrips-augmented plots.

Cotton fleahoppers. Woolly croton, with embedded overwintering fleahopper eggs, was harvested from rangeland sites near College Station, Texas, in early February 2018 and then placed into cold storage. Eighty 1-gallon sheet metal cans, each containing 4 ounces of dry croton twigs per can, were initiated to generate the required number of cotton fleahopper nymphs for the experiment. Conditions conducive to cotton fleahopper emergence were simulated in a laboratory environment in order to induce hatching of overwintered eggs embedded in the croton stems, and emerged cotton fleahoppers were subsequently reared on fresh green beans. The single release of nymphal cotton fleahoppers (2nd instars) was timed to simulate the acute heavy infestation of cotton fleahoppers (4-5 days of feeding) while cotton was highly vulnerable to the fleahopper injury (1st week of squaring). The release was accomplished on 10 July 2018 by transferring second-instar fleahopper nymphs from the laboratory colony into 15 cm X 10 cm plastic containers, then cautiously depositing them onto the terminals of plants in each treatment plot at the rate of 5 nymphs per plant. Immediately after cotton fleahoppers were released onto the fleahopper-augmentation plots (treatments #3 and #4; total 16 plots), control plots were sprayed with Orthene® 97. All treatment plots, except treatment #1, were sprayed with Orthene® 97 on 17 July 2018 and kept insect-free for the remainder of the study to isolate the effect of various treatments.

Insect augmentation: 2019 study

Thrips. Wheat cover was terminated on 20 May 2019 with glyphosate to facilitate thrips movement to emerging cotton seedlings to achieve natural infestation of thrips on experimental plots. Uncharacteristic heavy rain events during 23-26 May (4.51” rainfall) with associated small hail event compromised the study field for desired plant stand. Thrips were all dislodged from the wheat cover as well as those already transferred to cotton seedlings. Therefore, thrips were manually augmented on two 5-ft sections per treatment plots on 4 June 2019 via collecting immature thrips from nearby alfalfa terminals and releasing them onto the cotton seedlings, by placing thrips-infested alfalfa terminals at the base of each seedling @ approximately 5 thrips per cotton seedling. This rate of infestation is expected to result in about 1 thrips per seedling after

80% mortality of released thrips. Unexpected storms occurred on 5 and 6 May with additional 1” of rain dislodging all released thrips. We re-released thrips on 7 June 2019, but the ensuing hot and windy days following the second release did not allow thrips to colonize in the experimental plots. Consequently, we assumed no thrips effect on our experimental plots. Nevertheless, we conducted the visual ranking of the experimental plots on 11, 17, and 22 June 2019 to discern if any thrips-induced injury was inflicted on the seedlings. We found no thrips-inflicted injury nor observed any thrips colonization.

Cotton fleahoppers. Woolly croton, with embedded overwintering fleahopper eggs, was harvested from rangeland sites near College Station, Texas, 18 February 2019 and then placed into cold storage. Eighty 1-gallon sheet metal cans, each containing 4 ounces of dry croton twigs per can, were initiated on 10 May 2019 to generate the required number of cotton fleahopper nymphs for the study. Conditions conducive to cotton fleahopper emergence were simulated in a laboratory environment in order to induce hatching of overwintered eggs embedded in the croton stems, and emerged cotton fleahoppers were subsequently reared on fresh green beans. Cotton fleahopper emergence began on 19 June 2019. The single release of nymphal cotton fleahoppers (2^{nd} instars) was timed to simulate the acute heavy infestation of cotton fleahoppers (4-5 days of feeding) while cotton was highly vulnerable to the fleahopper injury (1^{st} week of squaring). The release was accomplished on 4 July 2019 by transferring second instar fleahopper nymphs from the laboratory colony onto the terminals of plants in each treatment plot at the rate of 5 nymphs per plant. Control plots had no insect activity to warrant any insecticide intervention. Unfortunately, a heavy rainfall occurred on 6 July 2019 (2.75”) and dislodged the released cotton fleahoppers and the treatment deployment was totally ineffective. The field was too wet to re-augment the cotton fleahopper within the next 2-3 days, but another storm passed through west Texas on 11 July 2019 that brought a damaging hail onto our field, causing significant damage to the test plots. Consequently, the crop stand was very poor with significant hail damage to the growing terminals for the crop to perform normally. Nevertheless, we introduced a manual square-removal treatment to selected control plots to evaluate the simulated fleahopper-induced square removal and resulting crop growth profile across three irrigation treatments. However, the unusual rainfall patterns might have already compromised our irrigation treatments. Treatments #1 and #3 were sprayed with BRACKET® 97 (acephate 97%) @ 3 oz./acre on 7 and 17 June 2019 to ensure insect-free plots to isolate the effect of insect-release plots. Square removal treatment was deployed on 26 July 2019 by removing 100% squares from all plants in two 5-row ft sections per plot.

Parameters measured

2018 study. The flowering profile was monitored from all 40 experimental plots for five sample dates (31 July, 6 August, 9 August, 15 August and 28 August 2018) to determine the effect of insect infestation and water deficit condition on fruiting delays and/or flowering patterns. Plant height was also recorded from all plots at the time of harvest. Hand harvesting was done on 16 November 2018 from flagged area and cotton was ginned on 17 December 2018. Lint were sent to Cotton Incorporated for fiber analysis.

2019 Study. As noted previously, thrips-released plots were visually inspected three times (11, 17, and 22 June 2019) to assess for thrips colonization as well as to rank for any thrips-induced injury to the seedlings. There was no evidence of thrips colonization nor any thrips-induced injury in our experimental plots. Cotton fleahoppers were also dislodged by heavy rain and probably did not cause injury to the growing squares, but we conducted the plant mapping 10 days after cotton fleahopper release to assess the fruit set on all experimental plots. We also monitored flowering profile by counting number white flowers in two 5-row ft sections per experimental plots twice a week (23, 26, and 30 July, 2, 5, 9, 12, 16, 19, 23, 26, and 30 August, and 3 and 11 September) during the cotton flowering period (total 14 sample dates). Pre-harvest plant mapping was done on 30 October 2019 and hand harvesting was done on 1 November 2019 from flagged area. Cotton was ginned on 14 November 2019 and the lint samples were sent to Cotton Incorporated for fiber analysis.

RESULTS

2018 study

Extremely high temperatures during the seedling stage complicated the study in 2018, especially the released thrips failed to exert the desired significant infestation on the young cotton seedlings. As a result, thrips damage to seedlings was not apparent on visual observation. Cotton fleahoppers caused about 20% square loss overall across all experimental plots. Because cotton fleahoppers were released when plants had 2-3 total squares (all were fleahopper susceptible squares), the effect was not apparent immediately and plants outgrew the effect of early season fleahopper-induced square loss. Nevertheless, insect injury manifested some noticeable effect on flowering patterns, plant height, and lint yield.

Untreated control plots showed slightly higher flower densities in irrigated versus dryland cotton effect all throughout the month-long monitoring period, with significantly higher flower densities in late August. Contrasting to this phenomenon, the flowering patterns were near identical between irrigated and dryland plots when cotton fleahoppers were infested singly or sequentially with thrips infestation (Fig. 1). When thrips were infested alone, flowering patterns between dryland and irrigated main-plot treatments were generally similar to what was observed in untreated or sprayed control plots. Overall, average flower abundance was similar across five insect augmentation treatments within each irrigation treatment (Fig. 2). While cotton flowering occurs daily during the active flowering period and the average of flower monitoring only five times may not reflect the production potential of cotton, these patterns clearly indicate that insect infestation, particularly cotton fleahoppers, rendered overall flowering patterns between irrigated and dryland similarly (Figs. 1-2). The average flower abundance was significantly lower in dryland compared to that in irrigated cotton only at untreated control plots while all other treatments were not significantly different between the two irrigation regimes (Fig. 2). These data suggest that the insect infestation during pre-flower stage exerts some significant physiological response to cotton during the flowering stage. Multi-year data will hopefully add more insights into this phenomenon.

Pre-harvest plant measurement showed that insect-augmented plots in irrigated cotton had significantly taller plants compared to that in untreated control plots, but the effect was considerably diminished under dryland conditions (Fig. 3). There was significant “noise” on plant height data under dryland condition in which fleahopper-infested plants resulted in the tallest plants while thrips followed by fleahoppers resulted in the shortest plant heights. We find no reasonable explanation for why cotton fleahopper-infested plots resulted in both tallest and shortest plants.

Lint yield was significantly higher in irrigated cotton compared to that in dryland cotton across all five treatment combinations (Fig. 4). This suggests that the dryland plots were sufficiently water-stressed during the growing season, despite several rainfall events during the crop maturation phase in late September - early October. The highest lint yield under irrigation treatment was observed in the untreated control treatment (1,607 lb/acre), while the lowest (1,253 lb/acre) was recorded in the thrips+fleahopper sequential infestation treatment (Fig. 4). Lint yield in other treatments (spray control, thrips only, and fleahoppers only) did significantly differ from the untreated control or thrips+fleahopper sequential treatments (Fig. 4). Lint yield did not significantly vary across five insect augmentation treatments. As expected, the yield threshold in dryland cotton was much lower than that for irrigated cotton and thus the lower yield across all treatments can be partially attributed for lack of insect treatment effect on lint yield.

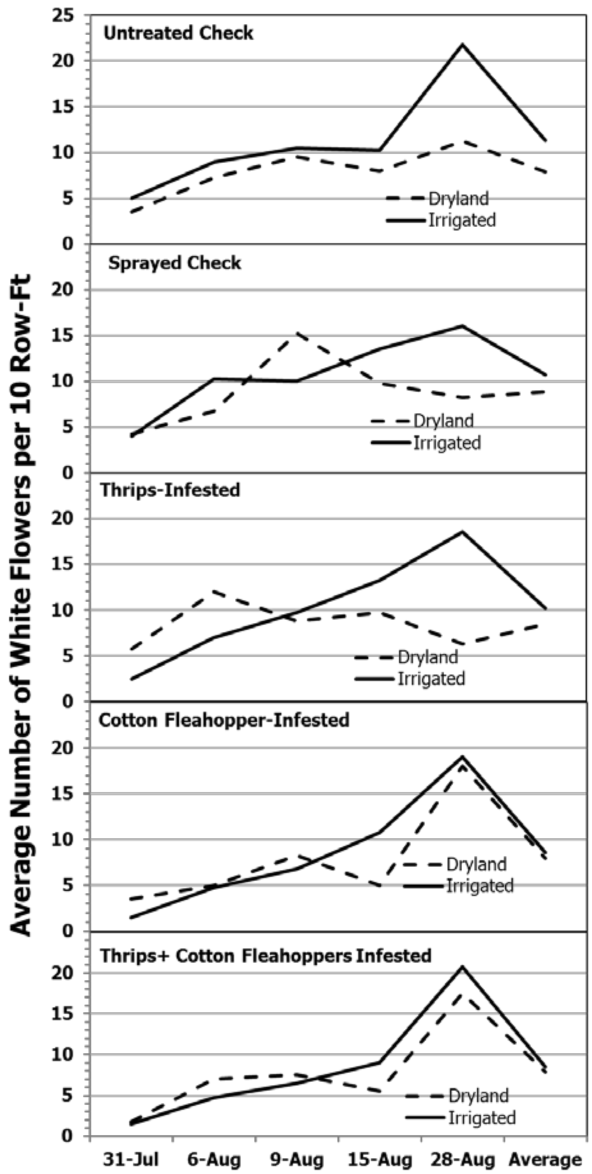

Figure 1. Temporal abundance of white flowers (number of white flowers per 10 row-ft per sample date) recorded from thrips and fleahopper infested plots under dryland versus irrigated production conditions, Lubbock, Texas, 2018.

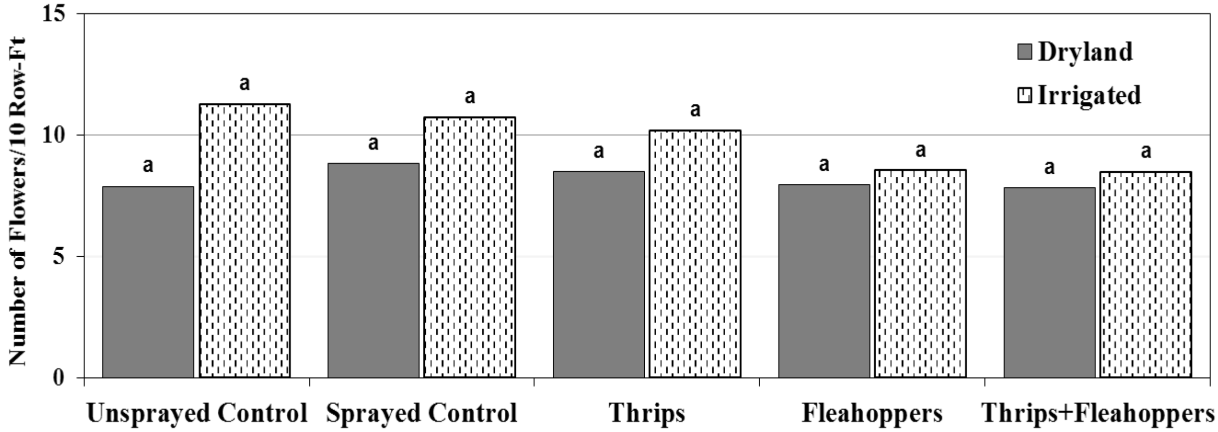

Figure 2. Average abundance of white flowers (number of white flowers per 10 row-ft; n=5 sample dates) recorded from thrips and fleahopper infested plots under dryland versus irrigated production conditions, Lubbock, Texas, 2018. Average values were compared across five treatments within each irrigation treatment; same lowercase letters indicate treatment means were not significantly different from each other.

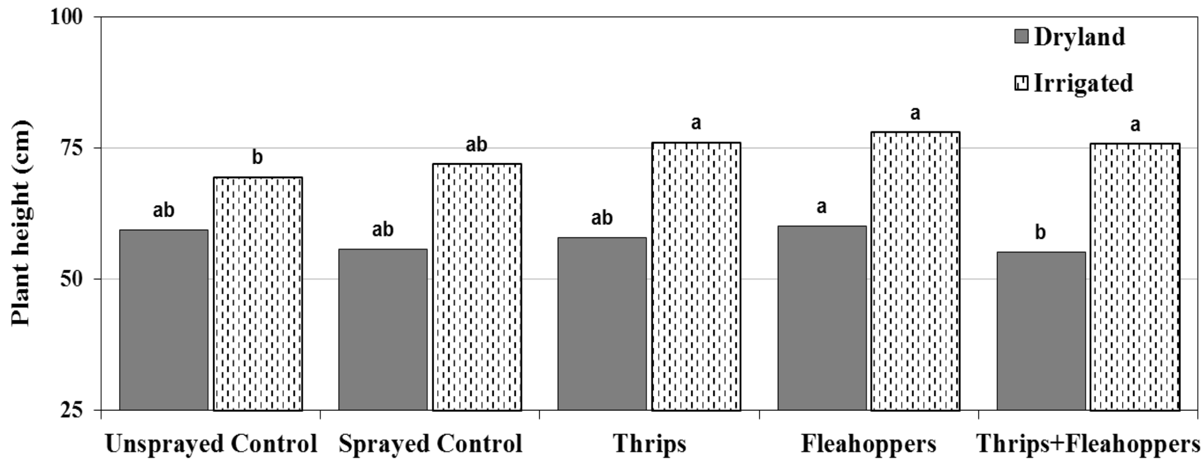

Figure 3. Plant height impacted by thrips and fleahopper infestations under dryland versus irrigated production conditions, Lubbock, Texas, 2018. Average values were compared across five treatments within each irrigation treatment; same lowercase letters indicate treatment means were not significantly different from each other.

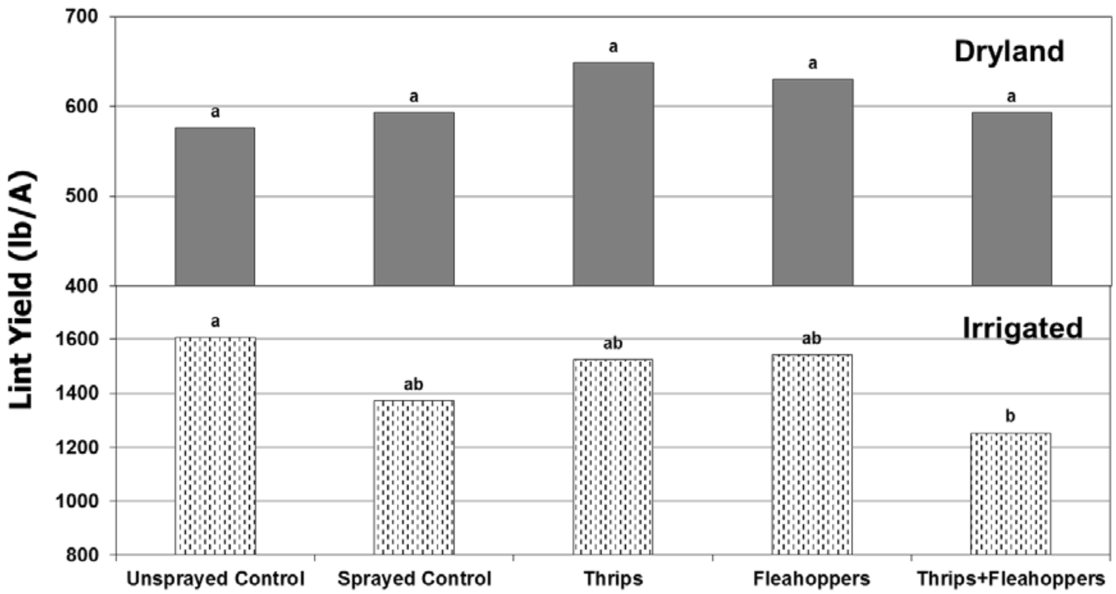

Figure 4. Cotton lint yield losses due to thrips and fleahopper infestation under dryland versus irrigated production conditions, Lubbock, Texas, 2018. Average values were compared across five treatments within each irrigation treatment; same lowercase letters indicate treatment means were not significantly different from each other.

2019 study

Atypical heavy rain events during the pre-squaring stage of cotton with associated small hail event compromised the early season portion of the study. Thrips were all dislodged from the wheat cover as well as those already transferred to cotton seedlings. Manually augmented thrips also suffered from recurring storm events and thrips could not colonize in the study plots. As stated in the Methods section above, we effectively abandoned the possibility of exerting thrips-induced injury effect on seedling cotton. Visual ranking of the experimental plots indicated no evidence of thrips-inflicted injury nor we observed any thrips colonization.

Cotton fleahopper augmentation resulted in 50-55% square abortion compared to 15-20% abortion in control plots; square abortion was similar between dryland and full irrigation plots (Fig. 5). While significant weather events occurred soon after cotton fleahoppers were released, the fleahopper augmentation exerted significant square loss as desired.

Untreated control plots and sprayed control plots showed higher flower densities in both irrigated and dryland cottons compared with that in insect augmented plots; this difference was more pronounced in irrigated plots than in dryland plots (Fig. 6). Full irrigation and supplemental irrigation plots displayed similar flowering patterns throughout the season. The plots with manual square removal to mimic cotton fleahopper-induced square loss displayed synchronized fruiting patterns across irrigation treatments. Overall, average flower abundance was similar amongst unsprayed control, sprayed control, and manual square removal plots, whereas the flower abundance on these three treatments were generally higher than that in all other insect augmented treatments; this trend was similar across all three irrigation water levels (Fig. 6). These patterns clearly indicate that insect infestation, particularly cotton fleahoppers, rendered overall flowering patterns between irrigated and dryland similarly. The average flower abundance was significantly lower in dryland compared to that in irrigated cotton at control plots while other treatments were not consistent across water treatments. These data suggest that the insect infestation during pre-flower stage exerts some significant physiological response to cotton during the flowering stage.

Pre-harvest plant measurement showed that insect augmentation treatments did not result in increased plant heights as observed in 2018. It was expected because the early rain/hailstorm events had severely thinned out the plant stand which allowed plants to grow laterally rather than adding the mainstem nodes following insect infestations. Nevertheless, plots in irrigated cotton had significantly taller plants compared to that in dryland plots as expected.

Lint yield was significantly higher in irrigated cotton (both full and supplemental) compared to that in dryland cotton across all five treatment combinations (Fig. 7). This suggests that the dryland plots were sufficiently water-stressed during the growing season, despite several rainfall events during the early to mid-season; there was a noticeable drought condition during the latter part of the growing season. The highest lint yield under full irrigation treatment was observed in the untreated control treatment (1,268 lb/acre), while the lowest (883 lb/acre) was recorded in the fleahopper infestation treatment (Fig. 7). These were the only treatments that resulted in significant yield difference. Lint yield did not significantly vary across insect augmentation treatments. Under dryland condition, lint yield did not significantly vary across treatments. As expected, the yield threshold in dryland cotton was much lower than that for irrigated cotton and thus the lower yield across all treatments can be partially attributed for lack of insect augmentation treatment effect on lint yield. Also, lint yield was generally similar between supplemental and full irrigation main treatments, owing to frequent rainfall events during early and mid-season that provided sufficient moisture profile in root zones in supplemental irrigation plots to carry the crop's water demand through the season. Thrips only treatment resulted in significantly lower yield under supplemental irrigation compared to that in other treatments (Fig. 8). However, we are unable to speculate the reason for this yield reduction since there were no visible thrips injury during the early growth period of the crop.

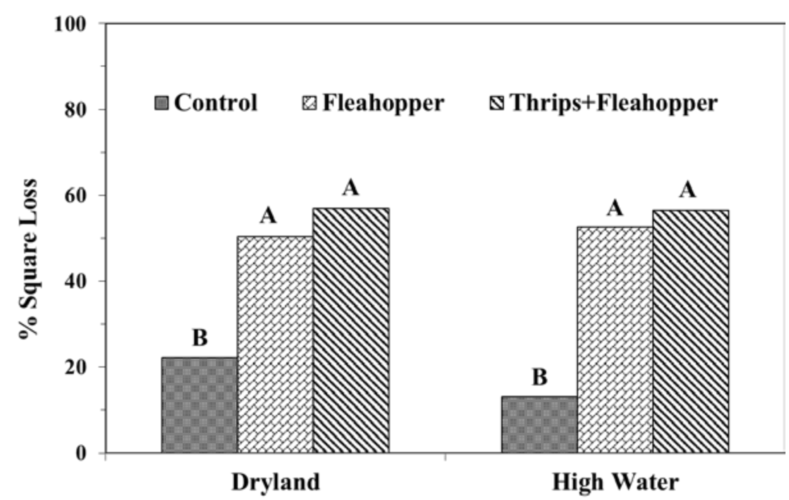

Figure 5. Percentage square loss (number of missing squares with respect to total squares set per plant) recorded following cotton fleahopper infestations in dryland versus full irrigation production conditions, Lubbock, Texas, 2019.

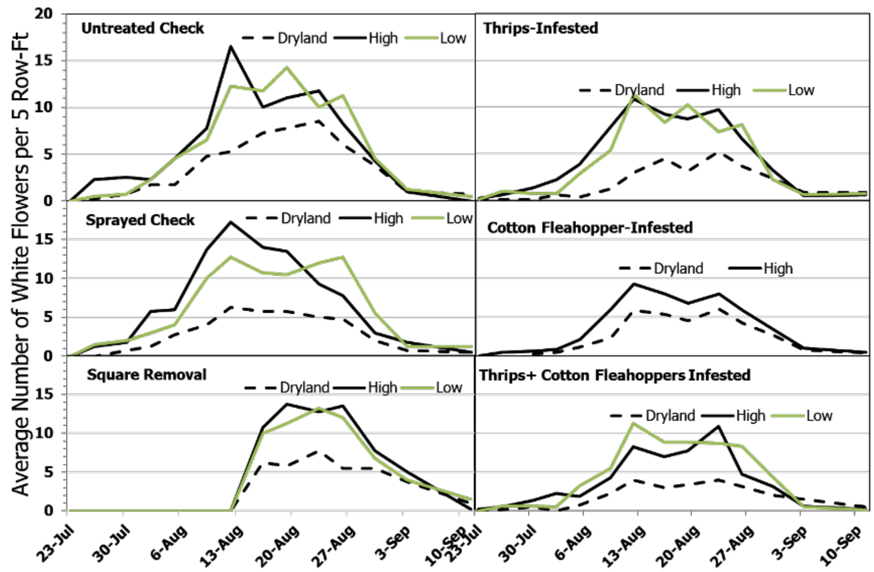

Figure 6. Temporal abundance of white flowers (number of white flowers per 5 row-ft per sample date) recorded from insect-release treatment plots under dryland, supplemental (low), and full (high) irrigation production conditions, Lubbock, Texas, 2019.

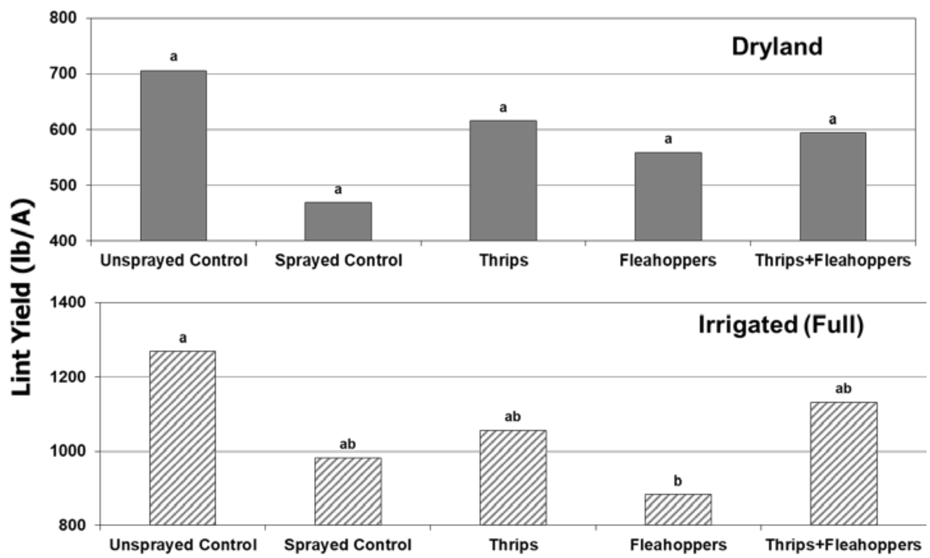

Figure 7. Cotton lint yield losses due to thrips and fleahopper infestations under dryland versus full irrigation production conditions, Lubbock, Texas, 2019. Average values were compared across five treatments within each irrigation treatment; same lowercase letters indicate treatment means were not significantly different from each other.

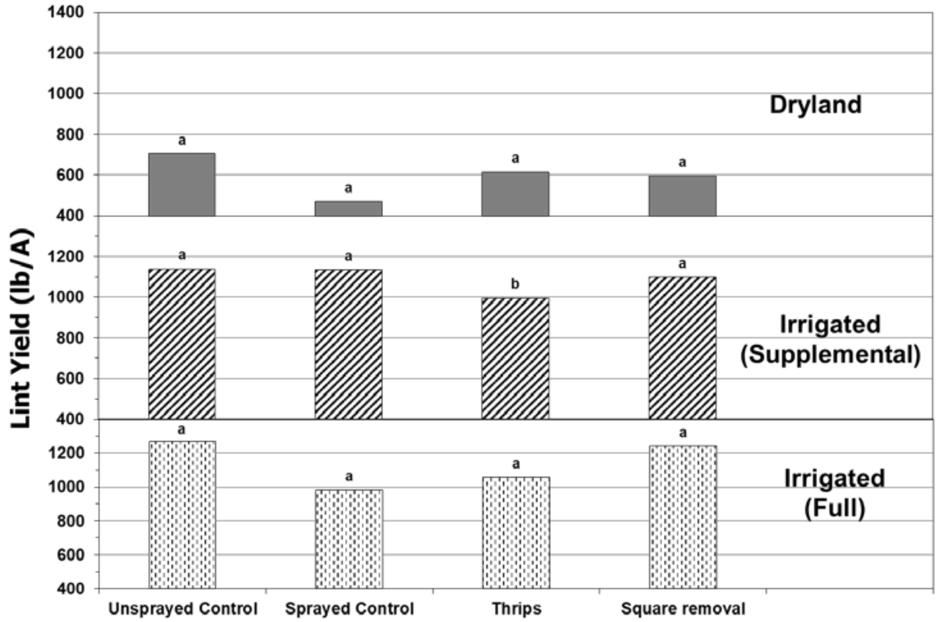

Figure 8. Cotton lint yield losses due to thrips and manual square removal (100% squares pruned at first flower stage to mimic severe cotton fleahopper damage) under three irrigation water regimes, Lubbock, Texas, 2019. Average values were compared across five treatments within each irrigation treatment; same lowercase letters indicate treatment means were not significantly different from each other.

We will begin developing the structure of the profitability model using these two years of data prior to planting the 2020 crop. These data will be used to analyze and compare the economics of management of thrips and cotton fleahoppers singly or in sequential combinations under two water-deficit production regimes. A set of economic profitability models will empower cotton producers in production decision-making in their specific production scenarios (insect pest management options in relation to water availability in their production enterprise). Economic decision-making models will be developed based on crop yield response and crop budget analyses. Crop yield response functions will be generated for each of the 5 insect management treatments within each water-deficit production systems, with 10 separate production scenarios. Cotton yield response to each insect treatment under two water levels will be fitted to calculate the slope (coefficient) of each treatment. Functional form will consider cotton yield and insect exposure (treatment) as fixed effect, and year as random. Insect management treatments within each water level will be ranked based on likelihood ratio test. Although the last two years of data were highly variable and inconsistent between the years, we expect that these data will help us develop the foundation of the model and the additional years of data will aid in refining the management model.

Acknowledgments

Research funding which facilitated this study came from Cotton Incorporated Texas State Support Committee. Dol Dhakal and Ziyan NanGong provided the technical help.

IMPACT OF *LYGUS* BUGS ON COTTON FIBER YIELD AND QUALITY UNDER SUPPLEMENTAL AND FULL IRRIGATION PRODUCTION CONDITIONS

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Abstract

The impact of late season *Lygus* infestation on cotton yield and fiber quality was assessed under supplemental and high irrigation regimes. Two cotton varieties and two *Lygus* densities were evaluated using field cages. Cages were removed a week after release of bugs and plants were sprayed with an insecticide to achieve an acute infestation. In another study, 20% bolls were removed from the top third of the plant to mimic late season *Lygus* infestation. The study revealed that the impact of *Lygus* injury was more pronounced under water-deficit growing conditions; likely because late-season lint yield compensations were limited due to reduced water availability limiting continued boll growth and fiber development. *Lygus* bugs significantly reduced lint yield both in supplemental and full irrigated cotton; however, cotton in water-deficit condition was more severely impacted by *Lygus* than under fully irrigated cotton. Cotton variety DP 1823NRB2XF performed better both in supplemental irrigation and full irrigation treatments than DP 1830B3XF.

Introduction

Lygus appears to be an increasing concern for the Texas High Plains growers in recent years. *Lygus* bugs utilize >300 host species including cotton in the cotton growing regions of the United States. The shift in cotton production system from 60:40% irrigated:dryland to 40:60% in the last decade has altered the cotton production practices. This shift from irrigated to dryland farming warranted to manage cotton pests effectively to increase profitability. Plant bugs have a general inclination to attack the stressed plants and cause significant damage. Cotton plant responses to *Lygus* injury under a range of irrigation regimes remain uninvestigated. The overall goal of this study was to characterize the effects of drought conditions on *Lygus* infestation behavior and plant response to *Lygus* injury.

Materials and Methods

A multi-year study was conducted in a multi-factor split-plot randomized block design with two water levels (full irrigation vs supplemental irrigation) and two infestation levels (*Lygus* augmented versus control). In 2018, *Lygus* were collected from nearby alfalfa fields and released in cages. *Lygus* were released on one 3-ft cotton row section per plot. Multi-plant (5-7 plants) cages were used to contain the released insects. The control plots were flagged and sprayed with insecticides. One plant from each treatment was removed and processed for *Lygus* damage assessment. Number of fruits aborted and internal/external boll damage as well as number of damaged seeds per boll were recorded. In 2019, a 5-ft section was flagged, and 20% bolls were removed from the top third of the plant to mimic *Lygus* bug infestation. Plants within flagged area were harvested, and lint yield and quality were determined.

Results and Discussion

Lygus bugs significantly reduced lint yield both in supplemental and full irrigated cottons; however, cotton in water-deficit condition was more severely impacted by *Lygus* than under fully irrigated cotton. DP1820B3XF had numerically lower lint yield than DP1823NRB2XF in both supplemental and full irrigation treatments (Fig. 1). In cotton variety DP1820B3XF, percent yield reduction was 48% in supplemental irrigation while percent yield reduction in full irrigation was 31%; however, in DP 1823NRB2XF, percent yield reduction in supplemental irrigation was 23% while the reduction in full irrigation was 21%. Thus, DP1823NRB2XF performed better both in supplemental and full irrigation treatments in our production situation (Fig. 2). In 2019, significantly higher lint yield was recorded from control plots in full (high) water treatments than simulated treatments. No differences in lint yield was recorded amongst treatments in low (supplemental) water treatments (Fig. 3).

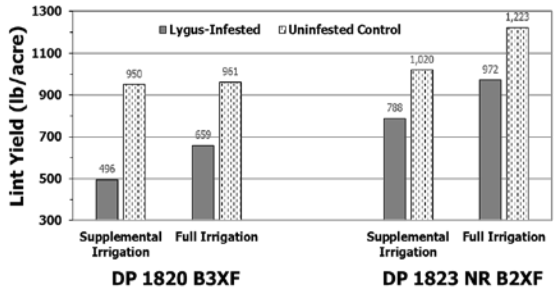

Figure 1. Cotton lint yield losses due to *Lygus* infestation under supplemental versus full irrigation production conditions, Lubbock, Texas, 2018.

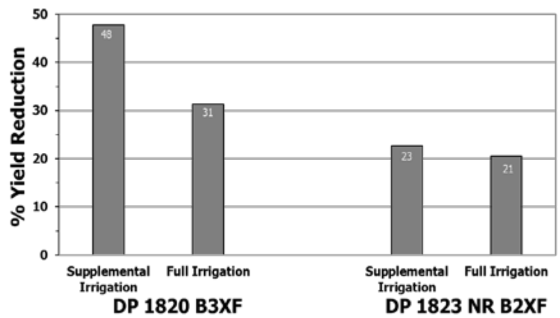

Figure 2. Percent lint yield losses in two cotton cultivars due to *Lygus* infestation under supplemental versus full irrigation production conditions, Lubbock, Texas, 2018.

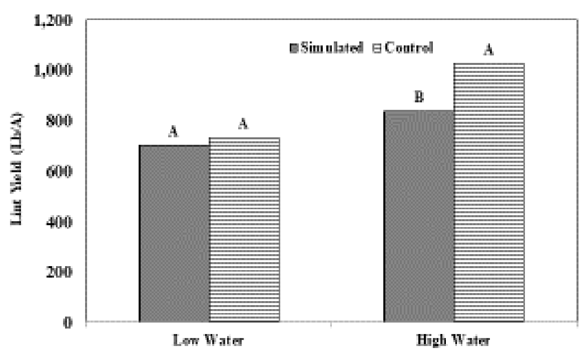

Figure 3. Cotton lint yield losses observed due to *Lygus* simulated damage under supplemental vs full irrigation, Lubbock, Texas, 2019.

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MANAGING EARLY-SEASON INSECT PESTS IN DRYLAND COTTON

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Abstract

A multi-year study has been initiated in the Texas High Plains to quantify the impact of single (thrips or cotton fleahoppers) versus multiple (thrips and cotton fleahoppers sequentially) pest infestations on cotton lint yield and fiber quality under two irrigation water regimes. The scope of this work entails integrating production practices and pest management options under numerous cotton management scenarios. Thrips and cotton fleahoppers were evaluated with five combinations of single versus sequential infestations under two water-deficit (near-zero deficit or full irrigation and high deficit or dryland) regimes, replicated four times. Thrips and cotton fleahopper augmentations and resulting colonization were compromised due to uncharacteristic rain and storm events. Plant growth parameters such as plant height, leaf area and dry leaf biomass were significantly higher in full irrigation plots than dryland plots. Water deficit conditions and insect infestations impacted crop growth profile as well as lint yield. Lint yield was similar across all five treatment combinations under dryland conditions while cotton fleahopper significantly reduced the lint yield compared to control under high irrigated condition.

Introduction

The Texas High Plains (THP) has been facing some significant unpredictable drought conditions in recent years. THP is a semi-arid region with characteristic low rainfall, with production agriculture supported by limited irrigation or rain-fed. As a result, the cropping system in this region is largely low-input and the producer decision-making in economically profitable input use is a challenge. Since 2007, water-deficit cotton production situation has worsened in THP and dryland:irrigated cotton production has shifted from 40:60 to 60:40 in recent years. Unpredictability of limited rainfall has been a challenge for cotton farmers in their production decision-making. Increased input costs and decreased availability of water have forced growers to move toward reorganizing available input resources to sustain their production enterprise.

Drought has direct and indirect effects on cotton, but the information on the effect of drought stress on cotton insect pest dynamics, feeding potential, and plant's response to insect injury under drought-stressed conditions are limited. Predicting pest populations under water-deficit cropping production scenarios and understanding how these conditions influence those populations to impact crop production risks are critically important components for implementing pest management strategies as crop cultivars and other input variables continue to change. The objective of this study was to quantify the impact of early-season pests on cotton lint yield and fiber quality under dryland and high irrigation water regimes.

Materials and Methods

Irrigation water level treatments

Two irrigation water levels (dryland and full irrigation) were evaluated in this study. A high-water treatment maintained >90% evapotranspiration replenishment through subsurface drip irrigation throughout the crop growing season whereas the dryland treatment received pre-planting irrigation to facilitate proper seed germination and no additional irrigation. Cotton cultivar DP 1646B2XF (seed with no insecticide or fungicide seed treatment) was planted on 14 May 2019.

Insect infestation treatments

Two key early-season insect-pest species (thrips and cotton fleahoppers) impacting cotton production risks were evaluated with five combinations of single versus sequential infestations under two water-deficit (zero versus high) regimes, including sprayed control and unsprayed control, replicated four times (total 40 experimental plots). Targeted insect management options were achieved via artificial infestation of insect pests as our experiment was designed to infest our treatments at the most vulnerable stage of crop for the species infested.

Insect augmentation

Thrips. Thrips were released to seedling cotton on 7 June 2019 when the crop was at 1-2 true leaf stage. Thrips infested alfalfa terminals were excised from a healthy alfalfa patch and these terminals were laid at the base of young cotton seedlings. Thrips were expected to move onto the cotton seedlings as excised alfalfa sections began to dry. Approximately 6 thrips per seedling were released to two 5 row-ft sections (approximately 12 plants per section) per plot (approximately 140 thrips per thrips-augmented plot), with 20% expected survivorship of released thrips.

Cotton fleahoppers. Woolly croton, with embedded overwintering cotton fleahopper eggs, was harvested from rangeland sites near College Station, Texas, in early February 2019 and then placed into cold storage. Eighty 1-gallon sheet metal cans, each containing 4 oz of dry croton twigs per can, were initiated to generate the required number of cotton fleahopper nymphs for the experiment. Conditions conducive to cotton fleahopper emergence were simulated in a laboratory environment in order to induce hatching of overwintered eggs embedded in the croton stems, and emerged cotton fleahoppers were subsequently reared on fresh green beans. The single release of nymphal cotton fleahoppers (2nd instars) was timed to simulate the acute heavy infestation of cotton fleahoppers (4-5 days of feeding) while cotton was highly vulnerable to the fleahopper injury (1st week of squaring). The release was accomplished on 4 July by transferring second-instar fleahopper nymphs from the laboratory colony into 15 cm x 10 cm plastic containers, then cautiously depositing them onto the terminals of plants in each treatment plot at the rate of 5 nymphs per plant. Immediately after cotton fleahoppers were released onto the fleahopper-augmentation plots, control plots were sprayed with Orthene® 97.

Parameters measured

The flowering profile was monitored from all 40 experimental plots for eight sample dates to determine the effect of insect infestation and water-deficit condition on fruiting delays and/or flowering patterns. Five plants from each plot were removed to record plant height, leaf area, and dry leaf biomass. Hand harvesting was done on 4 November 2019 from flagged area and cotton was ginned on 12 November 2019. Lint samples were sent to Cotton Incorporated for fiber analysis.

Results and Discussion

No significant differences were observed in thrips numbers between control-spray treatments and thrips-released treatments due to recurring storm events preventing thrips from effectively colonizing on the cotton seedlings. Plant parameters such as plant height, leaf area, and dry leaf biomass were significantly influenced by the irrigation water level, with greater plant height, larger leaf, and greater biomass in full irrigation plots compared to that in dryland plots (Figs. 1-2). As expected, lint yield was significantly higher in full irrigation treatments than dryland treatments. No significant differences in lint yield was observed amongst treatments in dryland plots; however, in irrigated plots, significantly higher lint yield was recorded from unsprayed control plots compared to that in fleahopper augmented plots (Fig. 3).

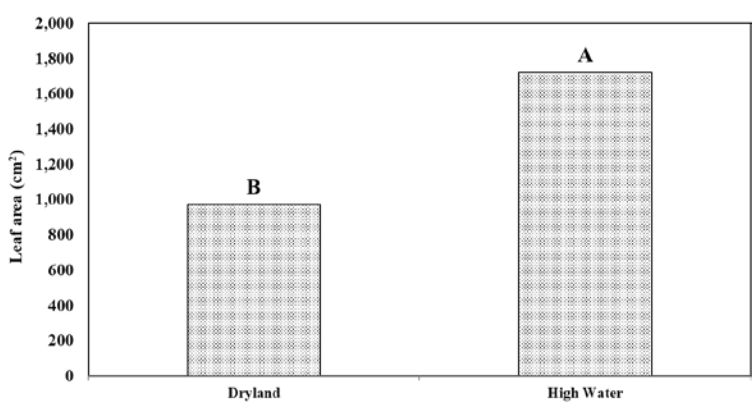

Figure 1. Leaf area recorded from dryland and high irrigation treatment plots, Lubbock, Texas, 2019. Different uppercase letters indicate treatment means were significantly different from each other.

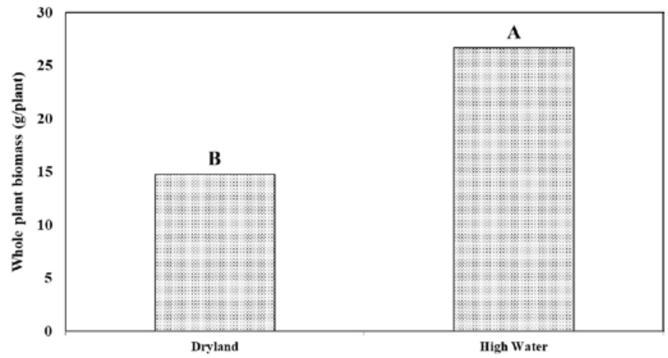

Figure 2. Plant dry biomass (peak-flowering stage) recorded from dryland and irrigation treatment plots, Lubbock, Texas, 2019. Different letters indicate treatment means were significantly different from each other.

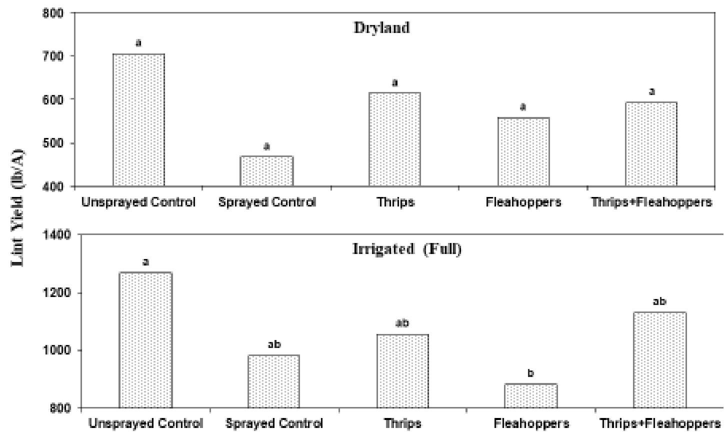

Figure 3. Cotton lint yield losses due to thrips and cotton fleahopper infestations under dryland versus irrigated production conditions, Lubbock, Texas, 2019. Average values were compared across five treatments within irrigation main treatment; same lowercase letters indicate treatment means were not significantly different from each other.

As noted previously, the 2019 crop season in the Texas High Plains was marked with uncharacteristic rain and thunderstorms which compromised our irrigation treatments. There was no evidence of thrips colonization nor any thrips-induced injury in our experimental plots. Cotton fleahoppers were also dislodged by heavy storms and probably did not cause injury to the growing squares as expected, but the plant mapping 10 days after cotton fleahopper release indicated significant square loss in fleahopper augmented plots. While no significant treatment differences were observed under dryland regime, cotton fleahopper augmented plots resulted in lowest yield under irrigated system. However, the yield was highly variable across treatments; thus, the results of the 2019 study are inconclusive. This study will be repeated for three additional years.

Acknowledgements

This study was supported by Cotton Incorporated Texas State Support Committee and Plains Cotton Improvement Program.

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EFFECT OF NITROGEN FERTILITY RATES ON COTTON CROP RESPONSE TO COTTON FLEAHOPPER DAMAGE

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Abstract

A long-term field study was conducted to examine the effect of soil nitrogen (residual nitrogen plus applied nitrogen) on cotton agronomic growth parameters and cotton compensation following cotton fleahopper induced fruit loss under a drip irrigation production system. Fixed-rate nitrogen application experimental plots, previously established and fixed for 12 years prior to the initiation of this study in 2014, consisted of five augmented nitrogen fertility levels (0, 50, 100, 150, and 200 lb/acre) with five replications. Each year, soil in each experimental plot was sampled for residual nitrogen analysis prior to planting. Rates of applied N exceeding 100 lb/acre resulted in 40-80 lb/acre residual nitrogen detection during the following season. Cotton fleahopper-induced fruit loss was generally compensated at low N as well as at high N, whereas optimum N was the most vulnerable to fleahopper-induced injury. Simulated fruit loss was generally compensated across all N application rates.

Introduction

Nitrogen fertility limits cotton production yields in the Texas High Plains. A Texas High Plains study under a limited irrigation production system (Bronson et al. 2006) characterized the effect of nitrogen application on leaf moisture and leaf nitrogen content in cotton and the resulting influence on cotton aphid population dynamics (Matis et al. 2008). Leaf nitrogen content did not vary with nitrogen application method (variable N versus blanket N application of an optimal amount), but both the blanket application and variable-rate application resulted in significantly higher leaf nitrogen contents than were noted in zero-augmented nitrogen plots. As nitrogen application rates were increased from zero to an optimum rate, a significant decrease in both aphid birth and death rates occurred, translating to a decrease in crowding and an increase in aphid survival (Matis et al. 2008). While these data help to characterize cotton aphid population dynamics between zero nitrogen fertility management and optimal nitrogen application rates, the population dynamics of cotton aphids and other cotton arthropods have not been examined under a full range of nitrogen fertility rates (Parajulee et al. 2006, 2008). In particular, no known study has produced plant growth parameters or fruiting profile data pertaining to a spectrum of nitrogen application rates in cotton. The objective of this study was to evaluate, in cotton growing under a subsurface drip irrigation production system, cotton crop growth parameters and cotton's ability to compensate for cotton fleahopper induced fruit loss as influenced by varying N fertilizer application rates.

Materials and Methods

The study was conducted at the Texas A&M AgriLife Research farm near Plainview, Texas. A 5-acre sub-surface drip irrigation system had been in place for 12 years prior to this study. Plot-specific nitrogen fertility treatments had been applied in a randomized block design with five replications since 2002. Five nitrogen application rates (0, 50, 100, 150, 200 lb/acre) had been deployed to the same experimental units consistently for 12 consecutive years to induce maximum discrimination among treatment plots through variation in soil residual nitrogen.

The study reported herein was conducted for six years (2014-2019). Soil residual nitrogen was monitored annually by taking two 24-inch core samples from each plot. The 0-12-inch portions of each core were combined to form a single, composite soil sample, and likewise, the 12-24-inch portions were combined, resulting in two samples per experimental plot. Samples were sent to Ward Laboratories, Kearny, Nebraska for analysis. Regionally well-adapted cultivars were used in this study over the duration of the study: FM 9063B2F was planted on 19 May 2014, FM 9180B2F on 18 May 2015, FM 1900GLT on 27 May 2016 and 4 May 2017, and NG3406 B2XF on 25 May 2018 and 4 June 2019. The experiment consisted of a randomized block design with five treatments and five replications. The five treatments included side-dress applications of nitrogen fertilizer at rates of 0, 50, 100, 150, and 200 lb

N/acre. Cotton was planted (56,000 seeds/acre) in 30-inch rows and was irrigated with a subsurface drip irrigation system.

Soil samples were taken from the experimental plots on 10 July (2014), 26 June (2015), 1 July (2016), 20 June (2017), 22 June (2018), and 26 June (2019) for residual nitrogen analysis. Crop growth and insect activity were monitored throughout the season. Fertility treatments were applied on 23 July (2014), 21 July (2015), 8 July (2016), 3 July (2017), 3 July (2018), and 19 July (2019) with a soil applicator ground rig. In 2014-2015, each plot received two cotton fleahopper treatments (5 adults per plant vs. no fleahopper as control), contained in multi-plant cages, within designated row sections two weeks into cotton squaring, the most critical phenological stage of cotton for fleahopper management in the Texas High Plains, to simulate an acute infestation of cotton fleahoppers. In 2016-2019, 100% squares were removed from treatment plots at first flower to simulate the cotton fleahopper induced square loss versus control (only data from 2018 and 2019 are included in this paper). Crop growth and fruiting patterns were monitored during the crop season. Pre-harvest plant mapping was done, and hand-harvested yield samples were obtained from each plot. Fiber samples were analyzed for lint quality parameters at the Cotton Incorporated Fiber Testing Laboratory (North Carolina).

Results and Discussion

Averaged over the entire 17-year study, soil residual N levels were significantly higher in plots that received the three highest application rates of N fertilizer versus plots receiving 50 lb/acre N or no N augmentation (Fig. 1). The highest N augmentation plots (200 lb/acre) had significantly highest average residual N (84 lb/acre); the year-to-year residual N was always the highest amount in this treatment, at least numerically. The two second highest N augmentation plots (100 and 150 lb/acre) resulted in significantly higher amount of soil residual N compared to that in zero and 50 lb/acre plots.

As expected, lint yield varied with N level regardless of the cotton fleahopper infestation. In uninfested control plots, lint yield displayed a characteristic staircase effect of nitrogen rate, with lowest lint yield in zero N and highest lint yield in 200 N treatments, with numerical increase in lint yield for each incremental nitrogen application of 50 lb/acre. Combined over all N treatments, the acute infestation of cotton fleahoppers rendered the lint yield reduction from 975 and 910 lb/acre in the uninfested control to 846 and 877 lb/acre in fleahopper augmented treatments in 2014 and 2015, respectively. In both years, cotton lint yield was not significantly affected by ~25% fleahopper-induced square loss three weeks into squaring at both zero N and 200 lb/acre plots, either via insect-induced pruning of undesirable fruit load (zero N) or compensation (200 lb N), whereas lint yield was significantly lower in fleahopper augmented 50 to 100 lb/acre plots (only 100 lb/acre treatment in 2015) compared to that in uninfested plots (Fig. 2), clearly suggesting that the plant response to cotton fleahopper injury is greatly influenced by nitrogen fertility. At 100 lb/acre N, plants were unable to compensate the cotton fleahopper-induced yield loss consistently in both years of the study, which may likely be attributed to N limitation (Fig. 2). On the other hand, simulated damage mimicking cotton fleahopper severe infestation (100% square loss at first flower) through manual pruning was generally compensated regardless of the applied N rates, except that there was a marginal reduction in yield at highest N levels in 2018 (Fig. 3).

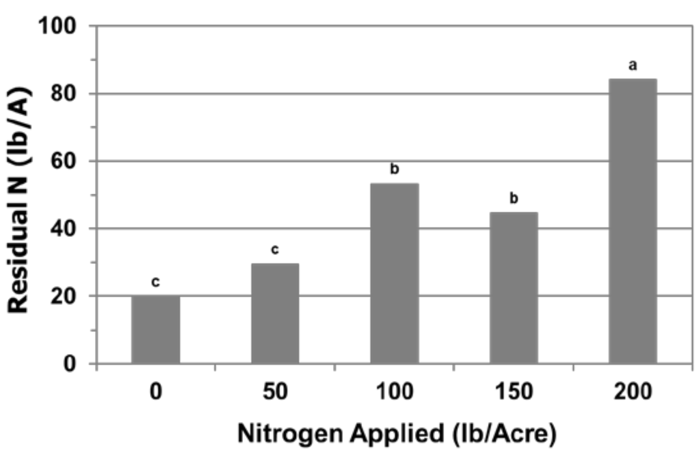

Figure 1. Average (2002-2019) yearly residual nitrogen as influenced by varying rates of applied nitrogen.

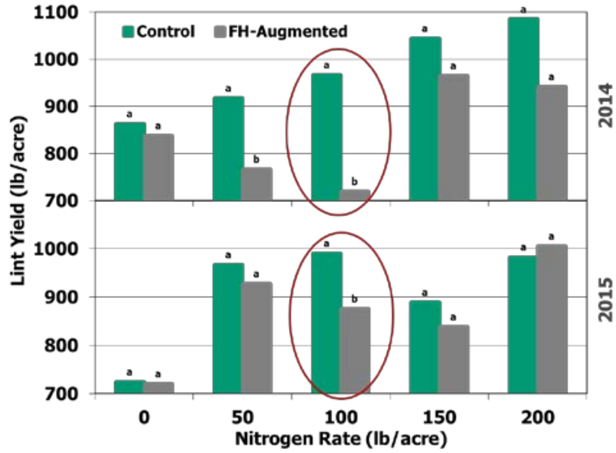

Figure 2. Effect of nitrogen augmentation rates on lint yield following a single acute infestation of cotton fleahopper versus uninfested control, 2014-2015.

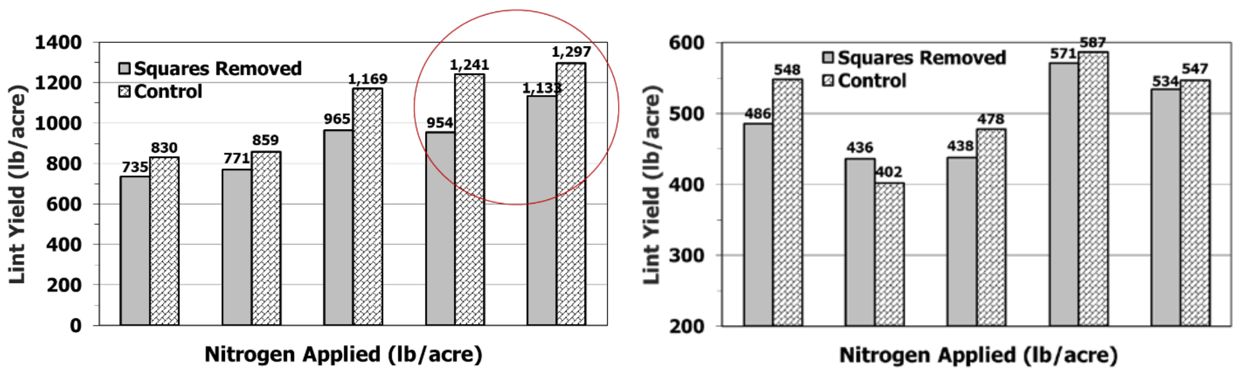

Figure 3. Effect of nitrogen augmentation rates on lint yield following a simulated severe infestation of cotton fleahopper versus uninfested control, 2018-2019.

Acknowledgments

Cotton Incorporated Core Program and Plains Cotton Growers, Inc. provided partial funding for this long-term nitrogen fertility study.

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Characterization of Intercrop Movement of *Lygus hesperus* between Cotton and Alfalfa

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ABSTRACT

Lygus hesperus Knight (Miridae: Hemiptera), a key pest of cotton in the United States, is a highly polyphagous insect. Upland cotton (*Gossypium hirsutum* L. var. *hirsutum*) and alfalfa (*Medicago sativa* L.) are two major field crop hosts of *Lygus hesperus* in the Texas High Plains. While alfalfa is considered a source of *Lygus* in cotton, *Lygus* intercrop movement behavior has not been fully characterized in cotton-alfalfa systems. Understanding the intercrop movement behavior of *Lygus* may facilitate better decision-making for *Lygus* management in these crops. A series of studies including a mark-release-recapture study and season-long field monitoring of *Lygus* were conducted in the Texas High Plains, USA. Season-long field marking and monitoring of *Lygus* intercrop movement revealed bidirectional *Lygus* movement and confirmed that *Lygus* preferred alfalfa over cotton. Net movement of *Lygus* between cotton and alfalfa was influenced by cotton phenology. A "two-crop/two-marker" field-marking and monitoring approach was successfully applied in characterizing *Lygus* seasonal intercrop movement. This approach can be used to study the effect of various crop management practices on *Lygus* intercrop movement and is applicable to other pests and cropping systems.

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1. Introduction

The "Push and Pull" strategy is an important component of integrated pest management (IPM) (Cook et al., 2007). The strategy of preserving sink habitats (trap crops) and destroying source habitats (alternate hosts) of insect pests is effective in reducing pest populations in field crops. Similarly, maintaining source habitats for predators and parasitoids increases biological control services (Khan & Pickett, 2004). While knowledge of source-sink dynamics of a pest population is valuable in formulating IPM strategies, determining whether a host acts as a source or a sink is challenging, especially when the pest species is highly polyphagous.

Lygus hesperus Knight, the western tarnished plant bug, is a highly polyphagous insect. It can survive and reproduce on a broad range of hosts (Day, 1996; Young, 1986). This species has been reported in 26 unique roadside weed hosts in the Texas High Plains (Parajulee et al., 2003; Parajulee, Shrestha, Barman & Carroll, 2008). Alfalfa is a primary host of *L. hesperus* in the Texas High Plains, particularly during the spring and early summer. Previous studies have demonstrated that *Lygus* prefer alfalfa over cotton and several other weed hosts (Sevacherian & Stern, 1974). Jackson (2003) reported that *L. hesperus* lay significantly more eggs (78%) in alfalfa than cotton. Past studies have also indicated that *Lygus* can move from alfalfa and other weed hosts into cotton (Fleischer, Gaylor & Hue, 1988; Sevacherian & Stern, 1975).

The severity of Lygus infestations in cotton depends upon local source-sink dynamics. For example, dispersal of Lygus populations from alfalfa to adjacent cotton could be encouraged by government-enforced mowing of roadside-growing "source" host species such as alfalfa. However, researchers in California have shown that strip-cutting commercial alfalfa fields prevents the dispersal of *L. hesperus* to cotton (Mueller, Summers & Goodell, 2005). Similarly, an areawide *Lygus* management project in Mississippi has demonstrated that roadside weed management is an effective means of minimizing tarnished plant bugs, *Lygus lineolaris* (Palisot de Beauvois), and bollworms in adjacent cotton. Expanding current knowledge of Lygus source-sink dynamics by quantifying the contribution of roadside-volunteer alfalfa to Lygus infestations in adjacent cotton could benefit Lygus management strategies.

Lygus can lay eggs and complete their life cycle in both cotton and alfalfa. Therefore, it is often confusing to determine whether roadside alfalfa is acting as a source or a sink for a Lygus population in an adjacent cotton field. In some alfalfa fields, large numbers of *Lygus* are found while

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very low numbers are detected in adjacent cotton. It seems logical, for such a scenario, to assume that alfalfa is acting as a sink for *Lygus*, potentially drawing them from cotton. While it is seemingly logical, such a conclusion may not be congruent with reality. Lack of consensus exists among researchers on the role of alfalfa in Lygus severity in adjacent cotton fields. In general, a higher density of *L. hesperus* in alfalfa than cotton might be due to a higher level of preference for oviposition in alfalfa than cotton. Carrière et al. (2006, 2012) reported alfalfa acted as a source of *L. hesperus* to nearby cotton fields; however, others reported alfalfa served as sink and reduced *L. hesperus* infestation in nearby cotton (Stern, Bosch & Leigh, 1964). A scientific approach characterizing the source or sink role of a weed host involves quantifying insect movement throughout the crop-growing season and determining their survival and reproductive success.

It has been reported that *L. hesperus* prefer laying eggs in alfalfa over cotton. If the mortality and survival rates are the same in both crops, then logically, alfalfa would be a source because of higher *L. hesperus* reproduction in this crop. However, the actual rates of reproduction, survival, and mortality of *L. hesperus* in these two hosts growing under actual field situations are not well understood. A source-sink relationship is a dynamic phenomenon, which can be affected by numerous factors, including competitors, predators, intercrop movement, environment, and host phenology. Also, because the realized niche of any organism is an n-dimensional hypervolume, it is inherently affected by many factors simultaneously. By elucidating the role of these factors, a greater understanding of the source-sink relationship between alfalfa and cotton can be characterized and better-informed pest management decisions can be made.

Suppression of roadside weed hosts (potential source of Lygus bugs) using herbicides reduced the level of Lygus infestation in adjacent cotton fields and reduced the application of insecticides in cotton in the Mid-South USA (Abel, Snodgrass & Gore, 2007). However, indiscriminate killing of roadside weeds using herbicide is not permissible in Texas. A common belief of producers and extension specialists in the Texas High Plains is that mowing and/or drying of roadside alfalfa and other weed hosts forces Lygus into adjacent cotton. If this is true, then a well-designed mowing strategy could be developed with the aim of "holding" Lygus in alfalfa and preventing their emigration to cotton. The vulnerability of cotton to Lygus injury changes with cotton phenological stages. It is more critical to manage *L. hesperus* during early boll development stages than in the boll maturation stage in the Texas High Plains (Parajulee, Adhikari, Kerns, Shrestha & Carroll, 2011). It is possible that the timing of alfalfa mowing can be managed to avoid or reduce *L. hesperus* movement during phenological stages of cotton critically vulnerable to Lygus. In addition, the application of biological control agents or pesticides on alfalfa strips prior to alfalfa mowing may reduce *L. hesperus* movement into cotton. A pest management practice that minimizes the movement of pest insects from source habitats into crop fields will reduce the amount of insecticides applied on the crop.

Sweep-net sampling has been used for the indirect assessment of contribution of weed hosts in the infestation of Lygus bugs in adjacent cotton (Cleveland, 1982; Parajulee & Shrestha, 2014). However, sampling *L. hesperus* without specific marking does not demonstrate actual movement between unique hosts. Stern and Mueller (1968) used micronized fluorescent powder to study movement of *L. hesperus*. Physical marking is labor intensive and potentially interferes with insect biology and behavior. Moreover, physical markers should be environmentally safe, scalable, cost-effective, and easy to use (Hagler & Jackson, 2001). Techniques involving insect protein marking and subsequent detection using enzyme-linked immunosorbent assay (ELISA) have been used successfully in studies involving insects such as *Hippodamia convergens* Guérin-Méneville (convergent lady beetle) (Bastola et al., 2016; Hagler, 2004; Hagler & Naranjo, 2004), *Pectinophora gossypiella* (Saunders) (pink bollworm) (Hagler & Miller, 2002), *Cacopsylla pyricola* Foerster (pear psylla) (Jones, Hagler, Brunner, Baker & Wilburn, 2006), *Pieris rapae* L. (cabbage worm) (Schmaedick, Ling, Gonsalves & Shelton, 2001), and thrips species *Thrips tabaci* Lindeman and *Frankliniella occidentalis* (Pergande) (Jasrotia & Ben-Yakir, 2006). Thus, it is presumed that this technique may prove satisfactory in evaluating *L. hesperus* intercrop movement in the Texas High Plains.

The objective of this study was to characterize intercrop movement behavior of *L. hesperus* to elucidate cotton-alfalfa source-sink dynamics, with an expectation that information generated would prove useful in *L. hesperus* pest management, specifically with regard to reducing *L. hesperus* movement from roadside alfalfa to adjacent cotton. This study was designed to evaluate *L. hesperus* host selection between alfalfa and cotton, the impact of alfalfa mowing on *L. hesperus* abundance in adjacent cotton, *L. hesperus* host preference and dispersal behavior, and season-long *L. hesperus* intercrop movement between alfalfa and cotton.

2. Materials and Methods

The study was conducted in Lubbock County (33.5779° N, 101.8552° W), Texas, which is located centrally in the Texas High Plains region of the United States. Two field experiments were conducted to characterize intercrop movement behavior of *L. hesperus* between cotton and alfalfa in the Texas High Plains during 2005-2008: 1) *L. hesperus* host preference under field conditions, and 2) Season-long monitoring of *L. hesperus* intercrop movement behavior.

2.1. L. hesperus Host Preference under Field Conditions

Because past field studies revealed that *L. hesperus* preferred alfalfa over cotton, it was hypothesized that more Lygus bugs would move from cotton to alfalfa than from alfalfa to cotton under natural field conditions, provided only the two host choices were available. In order to evaluate this hypothesis, two types of insect marking-recapture studies were conducted near Lubbock, Texas: 1) Mark, release, and recapture (MRR) using laboratory-marked field collected *L. hesperus* adults, and 2) Field marking, mowing, and capture (FMMC), an *in-situ* test of *L. hesperus* intercrop movement.

Mark, Release, and Recapture (MRR). A field experiment with two treatments (alfalfa and cotton) and three blocks was deployed in a strip-block design. A 12-row patch of alfalfa (1.02 m rows running north-to-south), measuring approximately 180 m x 12 m, was planted in the middle of a field and cotton was planted on both sides of alfalfa during the last week of April in 2007. Alfalfa and cotton fields were divided into three blocks measuring approximately 60 m x 12 m each. In August 2007, approximately 4,000 *L. hesperus* adults were collected from a nearby alfalfa field near Idalou, Texas. Active *L. hesperus* adults were externally marked with non-arthropod protein in the laboratory by nebulizing adults with the marker-protein solution for fifteen minutes. An Invacare® Envoy (Model RC1001) nebulizer was used to convert marker protein solutions to an aerosol. A 50% nonfat dry milk (NFDM) solution was used to mark 1,500 *L. hesperus*, while another 1,500 were marked using a 100% egg white (EW) solution. The bovine milk casein from NFDM and chicken egg albumin from EW served as the non-arthropod marker proteins.

EW-marked *L. hesperus* were released onto cotton plants at the center of each block at a rate of 500 adults per block. Similarly, NFDM-marked Lygus were released at the centers of alfalfa blocks at the same rate. Both releases were performed in the evening on the same day of collection. This study was conducted while cotton was in peak bloom, and alfalfa was in its post-blooming stage. Released Lygus adults were recaptured using a "Keep It Simple" or "KIS" sampler at 24- and 96-hours post-release. The KIS sampling device consisted of an Echo® model PB 265 backpack leaf blower (nominal airflow rating: 458 cfm) modified with an insect collecting net. Two KIS samples each covering 30 meters of row were collected from each block in each crop. Lygus samples were killed by freezing, sorted, and eventually stored individually in microcentrifuge tubes at -20°C for further processing via indirect enzyme-linked immunosorbent assay (ELISA). The detailed protocol for ELISA has been described in the *Indirect ELISA* sub-section below.

L. hesperus movement between crops was quantified based upon positive or negative to marker protein in ELISA. Lygus adults collected from alfalfa testing positive for EW protein were recorded as Lygus having moved from cotton to alfalfa. Similarly, all Lygus adults collected from cotton testing positive for NFDM protein were recorded as Lygus having moved from alfalfa to cotton. Net *L. hesperus* movement into cotton for each block was calculated by subtracting the number of emigrant Lygus bugs (those having moved from cotton to alfalfa) from the number of immigrant Lygus bugs (those having moved from alfalfa to cotton).

Field Marking, Mowing, and Capture (FMMC). Because the MRR study demonstrated the physical, "unidirectional" movement of Lygus bugs between alfalfa and cotton and the numbers of Lygus bugs marked and recaptured in the MRR study were too small to represent natural intercrop movement of Lygus bugs, a subsequent study using FMMC was conducted. A split-plot randomized block experiment with three blocks was designed. The main plot factors were two cotton growth stages: blooming and post-blooming (boll development). The subplot treatments were two hosts (cotton versus alfalfa). In July 2007, six field sites were selected in Lubbock County, Texas. Each site consisted of a long patch of blooming roadside alfalfa (>60 m in length) adjacent to a cotton field. Three sites were with blooming cotton and three sites with cotton at post-blooming stage. Sites were approximately 3 km apart. Each site represented an experimental block.

Alfalfa was sampled using a standard sweep-net (40-cm diameter) prior to the experiment to verify presence of *L. hesperus*. Thirty-meter long x 12 m wide alfalfa plots were marked using colored flags. Alfalfa plots received two high-volume spray applications of 10% NFDM with the intention of thoroughly drenching the alfalfa plants with the protein marker. Following alfalfa marking, the natural population of *L. hesperus* were allowed to forage for 24 hours, after which the alfalfa was mowed to a height of 12 cm with a tractor-mounted mower. A portion of the alfalfa plot was not sprayed and left uncut, hereinafter referred to as 'unmowed', to provide migrating Lygus with unmowed alfalfa as a host choice along with the adjacent cotton. The Lygus population was then allowed to forage, roam, and settle in its preferred host (unmowed patch of alfalfa versus cotton). Then Lygus adults were collected using a KIS sampler at 24 h and 96 h after mowing the alfalfa. While only one KIS sample, covering 30 m of row, was collected from unsprayed and unmowed alfalfa, four samples were collected from adjacent cotton (5^{th}, 10^{th}, 20^{th}, and 40^{th} rows, counting outward from the road into the field). More samples were collected from cotton to ensure that a sufficient number of marked Lygus would be collected for analysis by ELISA because Lygus population density is typically low in Texas High Plains cotton. Collected Lygus samples were killed by freezing, sorted, and stored individually in microcentrifuge tubes at -20°C for further processing via indirect ELISA.

Adult *L. hesperus* emigration from mowed alfalfa was determined by detecting NFDM marker protein adherence to Lygus via indirect ELISA. All Lygus adults collected from cotton or undisturbed alfalfa testing positive for NFDM protein were recorded as Lygus having emigrated from mowed alfalfa (where NFDM solution was originally applied). *L. hesperus* emigration from mowed alfalfa to cotton and to unmowed alfalfa was thus quantified.

2.2. Season-long Monitoring of L. hesperus Intercrop Movement

The intercrop movement of *L. hesperus* between cotton and alfalfa was monitored for seven weeks each in 2008 and 2009 cotton growing seasons. Field experiments were conducted at the Texas A&M AgriLife Research and Extension Center farm near Lubbock, Texas. *L. hesperus* intercrop movement was determined by field-marking of natural populations of Lygus adults in alfalfa and adjacent cotton field using two protein markers, capturing the adults using a KIS sampler, and detecting protein markers using indirect ELISA.

A field experiment was deployed in a randomized block design with two host crop treatments (cotton and alfalfa) and three blocks. A 12-row patch of alfalfa (measuring 180 m x 12 m) was planted in advance (30 April 2007) to establish an acceptable crop hosting a natural Lygus population. The alfalfa plot was adjoined bilaterally by cotton (cultivar FM 9063 B2F, Bayer Crop Science). Cotton was planted on 19 May 2008 and 22 May 2009. Alfalfa and cotton plots were divided latitudinally into three blocks measuring 60 m x 12 m each. Alfalfa blocks were arranged in a single long patch while cotton blocks were randomly assigned at either the north or south side of the alfalfa to facilitate crop-specific irrigation and cultivation requirements and weekly spraying of crop-specific marker protein.

Six weeks after cotton planting, the weekly spray applications of 10% EW marker solution in alfalfa and 10% NFDM marker solution in cotton were made for a period of seven consecutive weeks (from the initiation of cotton squaring to cotton boll maturation). KIS samples (covering 30 m x 1.02 m crop area) were collected from alfalfa and adjoining cotton fields 24 h after each field marking. In 2008, four KIS samples per week were collected from random locations within each block from each host for a period of seven weeks. In 2009, three samples were collected weekly from each block. Lygus adults collected by KIS sampling were killed by freezing and stored individually in microcentrifuge tubes at -20°C for further processing via indirect ELISA.

L. hesperus intercrop movement was determined based on the detection of externally applied insect protein markers in ELISA. Based on the ELISA results, Lygus adults were categorized into "immigrant," "resident," "roaming," and "visitor" groups. Lygus bugs from one crop host testing positive for only a protein marker applied in another host were categorized as "immigrants." Similarly, collected Lygus testing positive only for the protein marker applied to the collection source host were categorized as "residents." Lygus bugs testing positive for both protein markers were recorded as "roaming" insects. Lygus testing negative for both protein markers were recorded as "visitors," having migrated from a totally different source host outside these two crop hosts. Emigrant (outgoing) Lygus for alfalfa were considered as immigrant (incoming) Lygus for cotton and vice versa. For each host, net 24 h Lygus influx was calculated for each subplot by subtracting the average number of immigrant specimens from the number of emigrant specimens.

2.3. Indirect ELISA

An indirect enzyme-linked immunosorbent assay was performed for each sample to detect protein marker adhered on *L. hesperus* body. Antigen samples were prepared by incubating a Lygus sample in 300 µl of 1X Tris-Buffered Saline (TBS, 2.92 g NaCl + 2.42 g Tris + 1000 ml distilled water) in 2 ml microcentrifuge tubes at 4°C for 12 hours. Then, 80 µl of the antigen solution from each sample was added into a well of microtiter plate (Falcon 96 well Assay plate, VWR#62406-321) along with the same volume of known positive samples (n = 3) and negative samples (n = 8) and TBS control (n = 5). The 10% solution of NFDM or EW was used as positive control, *L. hesperus* without marker protein incubated in TBS as negative control, and pure TBS buffer without Lygus was used as TBS control. Then, the microtiter plate filled with antigen was incubated for an hour for binding antigen protein on the wall of microtiter plate well. The plates for testing NFDM were incubated at 27°C while the plates for testing EW were incubated at 37°C throughout this assay. After an hour of incubation, the plates filled with antigen were washed three times with Phosphate-Buffered Saline with Tween 20 (PBST). We used 2X PBST (i.e. 16.0 g NaCl + 2.28 g Na_2HPO_4 dibasic + 0.40 g KPO_4 monobasic + 0.40 g KCl + 999 ml distilled water +1 ml Tween 20) for washing plates and testing NFDM and 5X PBST (i.e., 40.0 g NaCl + 5.70 g Na_2HPO_4 dibasic + 0.60 g KPO_4 monobasic + 0.40 g KCl + 997.5 ml distilled water + 2.5 ml Twin 20) for washing plates and testing EW. After washing the excess unbound antigen, the inner surface of wells of microtiter plates not occupied with antigen was blocked by adding 180 µl of blocker protein and incubating for one hour for blocking the surface of the plate not covered by antigen. PBS with 1% Bovine Serum Albumin (BSA, Sigma-Aldrich # P3688) was used as blocker protein for testing EW, whereas 25% Egg white (All Whites, 100% Liquid Egg Whites, Crystal Farms, Walmart) diluted in 1X TBS was used for testing NFDM. The plates were again washed three times with 2X PBST to remove excess unbound blocker protein.

Immediately after washing excess blocker protein, wells were filled with 80 µl of primary antibody and incubated for 1 hour for binding primary antibody with the antigen protein. The primary antibody for testing NFDM was 1:2000 dilution of anti-bovine casein antibody produced in sheep (Biodesign International, #K20025) in blocker solution (25% egg white in 1X TBS). However, the primary antibody for testing EW was 1:8000 dilution of anti-chicken egg albumin antibody produced in rabbit (Sigma #C6534) in blocker solution (1% PBS-BSA plus Silwet @ 1.3 µl per ml). The plate filled with primary antibody was then washed three times with 5X PBST to remove excess unbound primary antibodies.

After removing excess unbound primary antibody, wells were filled with 80 µl of secondary antibody and incubated for one hour for binding secondary antibody with chain of antigen and primary antibody. The secondary antibody used for testing NFDM was 1:4000 dilution of anti-sheep IgG-peroxidase produced in donkey (Sigma #A3415) in blocker solution (25% egg white in 1X TBS). However, the secondary antibody for testing EW was 1:2000 dilution of anti-rabbit IgG-peroxidase produced in goat (Sigma #R2004) in blocker solution (1% PBS-BSA plus Silwet @ 1.3 µl per ml). Both secondary antibodies were conjugated with Sigma Horseradish Peroxidase enzyme. Then, excess and unbound secondary antibody was removed by washing three times with 5X PBST.

After washing excess unbound secondary antibodies, the wells were filled with 80 µl of the one component 3, 3', 5, 5'-Tetramethylbenzidine substrate (#TMBW-0100-04, BioFX Laboratory, Inc.) and allowed to complete reaction in room temperature. This reaction produced blue-colored reaction product. Following ten minutes of reaction time, the reaction was halted using 50 µl of TMB Stop solution (650 nm Stop reagent for TMB Microwell Substrates, BioFX laboratory, #LBSP), after which spectroscopy was performed on the microtiter plate, with absorbance readings taken at a light wavelength of 650 nm using a Stat Fax 3200 plate reader (Awareness Technology, Inc., FL).

Absorbance values or optical density (OD) data for each Lygus sample were then compared with a threshold OD value. The threshold OD value was calculated as the mean plus three times the standard deviation of the OD values for eight known negative samples tested on the same plate. The test sample was categorized as positive for the protein marker when the absorbance value (OD) of the test sample was equal to or greater than the threshold value. The samples with OD less than threshold value were categorized as negative for the tested protein marker.

2.4. Data Analysis

Data were analyzed with analysis of variance (ANOVA) using PROC MIXED procedure in SAS (SAS Institute, 2003). Means were separated using LSMEANS procedure at α=0.05. For the ANOVA of number of emigrant adults in the MRR study, the fixed effects included blocks, hours after release, host crop, and their interactions. The interaction between block and hours after release was a random factor. Two-sample one-tailed t-tests (PROC T-TEST, SAS Institute, 2003) were used separately for each phenological stage of cotton to test the effect of forced movement of Lygus adults from marked-and-mowed alfalfa to nearby undisturbed alfalfa versus adjacent cotton field. The effect of cotton crop phenology on Lygus intercrop movement behavior was determined by grouping the data from seasonal monitoring study into three cotton phenological stage categories: 1) cotton squaring (first, second, and third sampling weeks), 2) cotton blooming (fourth and fifth sampling weeks), and 3) cotton boll maturation (sixth and seventh sampling weeks). Data from each phenological stage category were averaged and the effect of cotton phenology on movement behavior (emigration, immigration, and net movement) was analyzed. The relationship between Lygus abundance in cotton and the number of immigrants from alfalfa was evaluated via correlation and regression analyses of the two-year combined data.

3. Results and Discussion

3.1. L. hesperus Host Preference in Field Condition

Data generated from the two-year MRR and FMMC studies were used to quantify the host preference and intercrop movement of *L. hesperus* between alfalfa and cotton as well as to assess the effectiveness of the protein marking technique in monitoring Lygus intercrop movement under natural field conditions.

Mark, Release, and Recapture. Analysis of variance of MRR data revealed significant effect of host crop (df = 1, 6; F = 13.53; P = 0.01) and there was no significant interaction (df = 2, 6; F = 0.94; P = 0.45) between host crop and time on the movement of marked *L. hesperus* adults. A total of 187 *L. hesperus* adults were captured in 540-m row of KIS sampling in cotton and alfalfa, of which 33% (62 adults) were from the group of marked-and-released *L. hesperus* adults. Lygus released in alfalfa were found in approximately equal amount in both alfalfa (24 resident adults) and cotton (21 immigrant adults) after a 24 h foraging period (Figure 1). This indicates that at the cotton blooming stage, Lygus adults moved from alfalfa to cotton. However, Lygus released in cotton were primarily recaptured in cotton (13 resident adults), while a few moved to alfalfa (4 immigrant adults) (Figure 1). A significantly higher number of immigrant adults were found in cotton than alfalfa (P<0.05; Table 1). The bidirectional movement of *L. hesperus* occurred between cotton and alfalfa during cotton blooming; however, the net movement was from alfalfa to cotton (17 adults from alfalfa to cotton) (Table 1). On average, more *L. hesperus*, including unmarked "visitor" insects, were captured in cotton than in alfalfa (Figure 1). This was true at both 24 h and 96 h after insect release. This was likely due to host quality because cotton was blooming while the adjacent alfalfa was senescing.

Table 1. Average (± SE) number of unidirectionally relocated protein-marked and released *L. hesperus* adults between alfalfa and adjacent cotton based on enzyme-linked immunosorbent assay of adults captured in samples covering 60-m of row per sample unit (n=3) in a mark-release-recapture study.

Foraging Time	Immigrant *Lygus* in cotton	Immigrant *Lygus* in alfalfa	Net Movement from alfalfa to cotton
24 h	7.0 ± 4.5 A	1.3 ± 0.7 B	5.7 ± 5.2
96 h	10.0 ± 2.6 A	2.0 ± 1.0 B	8.0 ± 3.6
Average	8.5 ± 1.5 A	1.7 ± 0.3 B	6.8 ± 1.2

Means followed by different uppercase letters were significantly different (P<0.05) between cotton and alfalfa within the same foraging time.

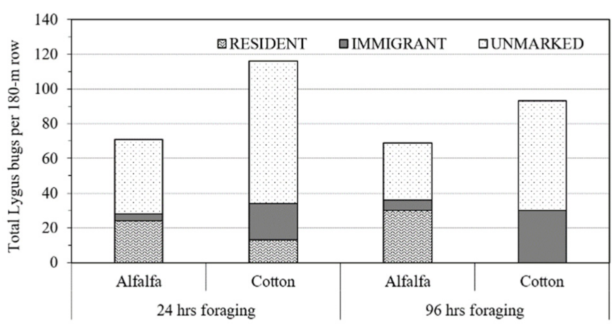

Figure 1. Categories of *L. hesperus* collected from blooming cotton and post-blooming alfalfa in mark-release-recapture study, Lubbock, Texas, 2008.

Of the total 3,000 *L. hesperus* adults released, only 62 (2%) were recaptured. Such a small percentage recovery could have resulted from rapid Lygus dispersal, or high mortality of marked insects caused by physical injury inflicted by sweep-net and aspirator use during collection. While Lygus mortality following field collection can be minimized by rearing them temporarily in a controlled environment and by specifically selecting healthy, uninjured insects for marking and release, this was not done in this study because laboratory rearing of field-collected insects using a food source and climate parameters to which they are unaccustomed could alter their host selection behavior.

Field Marking, Mowing, and Capture. In FMMC, roadside alfalfa was sprayed with NFDM marker solution. Twenty-four hours after marker application, the alfalfa was mowed resulting in most *L. hesperus* adults being forced to move and choose adjacent cotton or undisturbed alfalfa. When the roadside alfalfa was mowed, a significantly higher number of marked *L. hesperus* relocated to adjacent undisturbed alfalfa (85% at cotton blooming stage; 87% at cotton boll maturation stage) than to cotton (15% at cotton blooming; 13% at cotton boll maturation) (Table 2). It was anticipated that cotton phenology would reveal a more significant impact on *L. hesperus* movement into cotton from mowed alfalfa; however, this was not the case. In both phenological stages of cotton, fewer adults moved to cotton than to undisturbed alfalfa. However, due to possible attraction to abundant floral nectar, it was expected that more Lygus would migrate to cotton during blooming than during boll maturation. The number of migrant Lygus at cotton blooming stage and boll development stage cannot be compared directly because of the difference in Lygus densities between these two crop phenological stages. The total number of Lygus captured in alfalfa at cotton blooming stage was 4.7 times higher than at boll maturation stage. Similarly, the total number of Lygus captured in a cotton field at blooming stage was 3.8 times higher than cotton boll maturation stage (Figure 2). Previously published results have indicated a general decline in *L. hesperus* population during the time when cotton was typically maturing (Parajulee & Shrestha, 2014), and our data from FMMC study supported this observation (Figure 2). These observations made in FMMC study encouraged development of a new hypothesis regarding cotton-alfalfa source-sink dynamics with respect to *L. hesperus*. Thus, a season-long study was designed to test the effect of cotton phenology on the intercrop movement of *L. hesperus* between alfalfa and cotton.

Table 2. Average (± SE) number of immigrant *L. hesperus* adults found in cotton and undisturbed alfalfa (per KIS sample covering 30-m of row) 24 h after mowing of the adjacent protein-marked alfalfa.

Cotton phenology	Alfalfa	Cotton
Blooming	17.33 ± 8.99 A	3.00 ± 2.67 B
Boll development	11.33 ± 5.89 A	1.72 ± 0.43 B
Average	14.33 ± 4.99 A	2.36 ± 1.24 B

Means within each row followed by different uppercase letters are significantly different (one-tailed t-test; α=0.1).

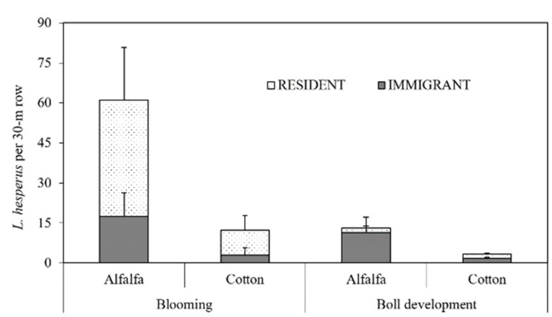

Figure 2. Prevalence of immigrant and resident *L. hesperus* adults in cotton versus alfalfa following the mowing of protein-marked adjacent alfalfa during the two phenological stages of cotton, Lubbock, Texas, 2008.

3.2. Season-long Monitoring of Lygus Intercrop Movement

Lygus Abundance. A total of 294 KIS samples were collected (147 from cotton and 147 from alfalfa) over 2008 and 2009. From these samples, a total of 1,273 adult *L. hesperus* were retrieved (580 in 2008 and 693 in 2009). There was no significant difference (df = 1, 2.17; F = 9.26, P =

0.084) in average seasonal Lygus abundance between 2008 (5.69 ± 0.85 bugs per sample) and 2009 (7.07 ± 0.66 bugs per sample). Numerically higher *L. hesperus* abundance in 2009 could be explained by a longer "window" for Lygus colonization in alfalfa. The alfalfa crop was one year older in 2009 than in 2008, and thus may have been better established and of generally higher quality. Host crop significantly affected the abundance of Lygus (df = 1, 25.2; F = 43.51; P = <0.0001), with 82% of the insects (1,111 bugs) found in alfalfa versus 13% in cotton (162 bugs). Lygus abundance varied significantly among the sampling weeks (df = 6, 18.8; F = 5.35; P = 0.0023). In 2008, significantly more bugs (24.5 ± 7.5 per KIS sample) were found in the second sampling week (the week of 20 July 2008) in alfalfa than in other weeks, but in 2009, the peak (20.56 ± 3.08 bugs per KIS sample) occurred during the sixth sampling week (the week of 20 August 2009). In cotton, average *L. hesperus* abundance was always relatively low (<3.5 bugs per KIS sample) and remained statistically similar across sampling weeks and among cotton phenological stages. Barman, Parajulee, and Carroll (2010) also demonstrated a lower rate of colonization of *L. hesperus* in cotton compared to that in alfalfa in a multi-host choice field study.

Temporal Dynamics of Intercrop Movement of *L. hesperus*. Bidirectional *L. hesperus* intercrop movement between alfalfa and cotton was evaluated using a "two fields/two markers" approach. Based on the results of ELISA performed on Lygus bugs retrieved via KIS sampling, all collected Lygus bugs were categorized as residents, immigrants, roamers, or visitors. All data are presented in terms of *number per ha* (Figure 3). Over two years, 162 Lygus bugs were retrieved from cotton. In 2008, 64% of bugs retrieved from cotton were verified as having at some point inhabited marked alfalfa. In 2009, this increased to 96%. These data clearly indicate that alfalfa had a Lygus source effect upon adjacent cotton.

Prior to this study, no satisfactory technique for quantification of actual net intercrop movement of a population of small insects during a specified duration had been developed. The "two fields/two markers" approach used in conjunction with ELISA for determination of insect origin is capable of clearly demonstrating both the direction and net balance of Lygus intercrop movement, following a specific foraging or roaming period (Hagler & Naranjo, 2004). However, this capability is limited to what could be described as a "snapshot" of the net balance and interpreted direction of movement at the time of sampling.

Because it is within the realm of possibility, and even probable, that *L. hesperus* moved back and forth between cotton and alfalfa during each foraging period (between marking and retrieval), the technique used is incapable of clearly characterizing the true dynamic, temporal fluctuation of *L. hesperus* intercrop movement. This aspect of the study is somewhat analogous to the difference between a photograph and a motion picture. The possibility that marked insects may have made "test flights," or temporarily changed hosts during the short foraging period, cannot be fully accounted for with the methods used. Despite this possibility, such an accounting of temporal movement fluctuation is not necessary in order to ascertain the vector and net balance of bidirectional Lygus intercrop movement, or more importantly, the net influx of Lygus into cotton from alfalfa. Given this limitation, and with no credible scientific rationale for doing so, no distinction was made between potential movement transience or permanence.

FMMC was the obvious technique of choice for a season-long intercrop movement study. It was selected for its effectiveness, efficiency, and practicality. MRR is commonly used in movement and migration studies (Hagler & Jones, 2010), but it is not feasible for use in a large-scale season-long intercrop movement study. The primary disadvantage of MRR is its usual small marked-recapture rate (2% with *L. hesperus*, as was discovered during the MRR study). Exposure to a laboratory environment, mass-rearing, handling, and marker application are all factors of MRR use which may interfere considerably with natural insect behavior.

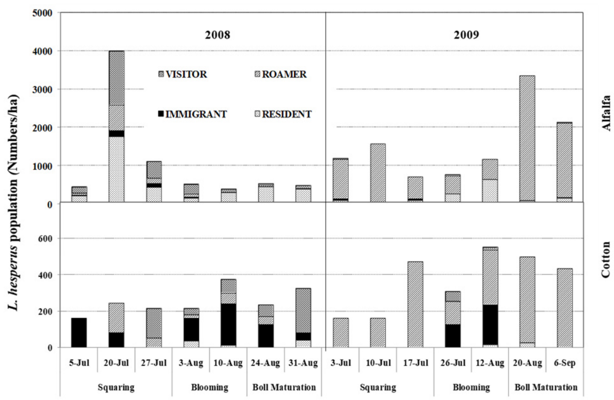

Figure 3. Temporal dynamics of *L. hesperus* immigrant, resident, visitor, and roamer populations in alfalfa and cotton, Lubbock, Texas, 2008-2009.

Correlation and regression analyses of verified total *L. hesperus* cotton influx (cotton-collected immigrants plus cotton-collected roamers) and total cotton-collected *L. hesperus* revealed a highly positive relationship (r = 0.98; n = 35; P = 0.0001; Figure 4a). One reason for combining cotton immigrants and roamers into the category of verified total *L. hesperus* cotton influx was the strong relationship between the number of roamers and the total number of *L. hesperus* collected (Figure 4a). The relationship between immigrant only and the total bugs collected was weak (Figure 4a). Regardless of the weakness or strength of these relationships, Lygus immigrants and roamers collected from cotton tested positive for EW protein, proving definitively that these insects had, at some point during the foraging period, inhabited EW-marked alfalfa. Examining immigrants alone does not address this critical fact and the circumstances of such habitation or origination, while interesting, and possibly explainable by the simultaneous presence of NFDM protein, are biologically irrelevant. The total number of *L. hesperus* found in cotton and total Lygus cotton influx shared a similar pattern (Figure 4b) until the last week of sampling in 2008. In 2009, their patterns were nearly identical. The pattern divergence in 2008 could have been due to a sudden flush of new adult emergence during the final week of sampling.

Analysis of variance of *L. hesperus* influx of both crops revealed significant differences in the pattern of *L. hesperus* intercrop movement between the two years (df = 1,3.32; F = 194.51; P = 0.0005), between two hosts (df = 1,24.6; F = 39.08; P = <.0001), and among the cotton phenological stages (df = 1,8; F = 22.12; P = 0.0006) and sampling weeks (df = 6,14; F = 12.31; P = <0.0001). The difference in the *L. hesperus* intercrop movement patterns in 2008 and 2009 was likely due to differences in alfalfa and cotton crop development because of differential rainfall between the two years. The 2009 cotton growing season was marked by greater rainfall, improving cotton and alfalfa crop growth and quality. As a result, *L. hesperus* densities were higher in both crops in 2009, except for one sample date in alfalfa in 2008 (Figure 5). We hypothesized that *L. hesperus* intercrop movement might have been affected by Lygus density in the source habitat (alfalfa), but correlation (r = 0.14; n = 42; P = <0.36) and regression ($R^2 = 0.02$; n=42; $P = <0.36$) analyses failed to reveal any significant relationship between alfalfa Lygus density and cotton Lygus influx.

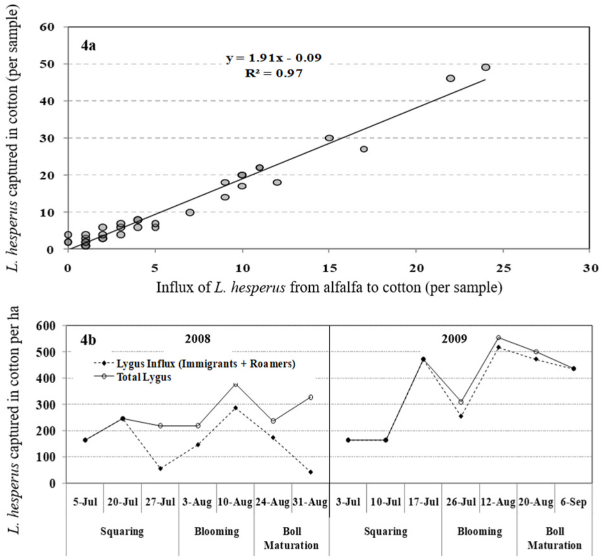

Figure 4. a) Relationship between total *L. hesperus* found in cotton and total *L. hesperus* influx from alfalfa to cotton, b) Weekly pattern of total *L. hesperus* and *L. hesperus* influx in cotton, Lubbock, Texas, 2008-2009.

During the first five weeks after cotton planting, *L. hesperus* were not detected in cotton. *L. hesperus* is typically a late-season pest of cotton in the Texas High Plains (Parajulee, Hakeem & Carroll, 2015). *L. hesperus* began to move into cotton from alfalfa once cotton began squaring. Until mid-July, all Lygus found in cotton (100%) were verified as having inhabited marked alfalfa (Figure 5). As the *L. hesperus* population increased in cotton, influx from alfalfa decreased. This was likely a dilution effect resulting from the emergence of new Lygus adults in cotton and influx of Lygus "visitors" from sources other than the protein-marked alfalfa.

Protein-marked alfalfa contributed significantly to *L. hesperus* population growth in adjacent cotton throughout the growing season. Net *L. hesperus* intercrop movement with respect to cotton in the cotton-alfalfa system was calculated by subtracting Lygus cotton influx (EW-marked *L. hesperus* captured in cotton) from Lygus cotton outflux (NFDM-marked bugs captured in alfalfa). Year (df = 1, 2; $F = 199.41$; $P = 0.0050$) and cotton phenology (df = 2, 32; f= 9.71; p= 0.0005) affected average *L. hesperus* net movement significantly (Figure 5). In 2009, average *L. hesperus* net movement was significantly lower (df = 2, 16; f= 10.82; p= 0.001) during cotton blooming (113 bugs per ha outflux) than during squaring (893 bugs per ha outflux) or boll maturation (2,161 bugs per ha outflux). In 2008, average *L. hesperus* net movement was significantly higher (df = 2, 16; $F = 3.64$; $P = 0.05$) during cotton blooming (161 bugs per ha influx) and boll maturation (70 bugs per ha influx) than during squaring (286 bugs per ha outflux). The influx-outflux disparity during cotton boll maturation between years may be partly explained by a slight sampling date incongruence between the two study years. Sampling was conducted slightly later in 2009, into the month of September, and inclusion of this later sampling date, which occurred during a typically pivotal period of crop senescence with regard to *L. hesperus* abundance, in the chronological categorization of boll maturation, may have influenced this disparity.

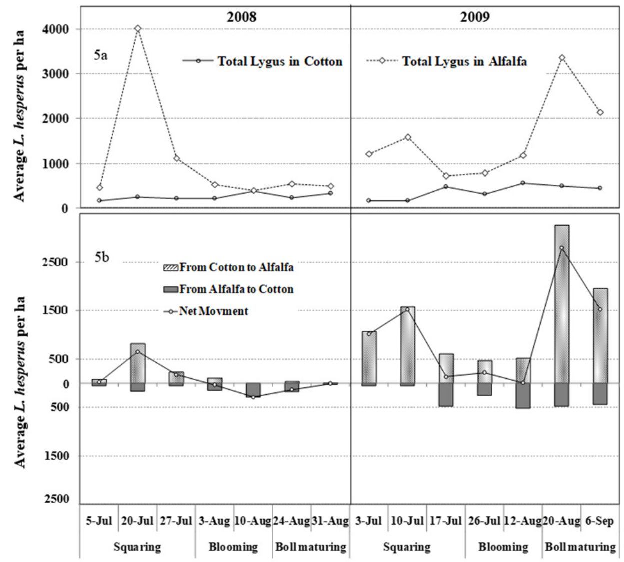

Figure 5. a) Weekly average *L. hesperus* abundance in cotton and alfalfa, b) Net *L. hesperus* intercrop movement between alfalfa and adjacent cotton, Lubbock, Texas, 2008-2009.

It is somewhat puzzling to have observed net movement favoring alfalfa while simultaneously observing increases in EW-marked *L. hesperus* retention and population in cotton (Figure 5). While *L. hesperus* retention in cotton was used as a component in net intercrop movement calculation, the data suggested that net intercrop movement and actual *L. hesperus* population change were weakly related. Actual Lygus population change in cotton is affected more by reproduction success (birth rate), developmental time, and mortality due to natural enemies. A single calculation of net *L. hesperus* intercrop movement, or an intercrop movement "snapshot" obtained on a single sampling date, in the context of this study, indicates only the instantaneous directional flow of insect intercrop movement at the time of sampling. It is the confluence of all snapshots which reveal patterns in the direction of net intercrop movement. Some interesting patterns revealed by this study were the relationships between net *L. hesperus* intercrop movement and *L. hesperus* population densities in cotton. When net *L. hesperus* movement favored cotton, there were strong positive relationships between net *L. hesperus* movement and average *L. hesperus* abundance in cotton. Average *L. hesperus* abundance in cotton also related strongly to net intercrop movement favoring alfalfa, but when net movement exceeded ~2,600 bugs/ha, *L. hesperus* density in cotton decreased drastically.

4. Conclusion

When both habitats are available in proximity, the *L. hesperus* intercrop movement data showed that alfalfa is a more preferred host than cotton for *L. hesperus* colonization (Barman et al., 2010). Despite this preference, alfalfa may dynamically confer both source and sink effects, with respect to *L. hesperus*, depending on crop phenology and host quality (Chen &

Parajulee, 2010; Parajulee et al., 2011; Parajulee et al., 2015). During cotton blooming, net *L. hesperus* intercrop movement between cotton and alfalfa favored cotton. This was true even without forced relocation of *L. hesperus* due to alfalfa mowing. Forced relocation of *L. hesperus* from alfalfa, induced by mowing, resulted in net *L. hesperus* intercrop movement favoring cotton through boll maturation.

During spring and early summer months, alfalfa is more suitable to *Lygus* spp. and it is preferred over cotton as a host (Barman et al., 2010; Chen & Parajulee, 2010; Stern et al., 1964). Carriere et al. (2006) found that a forage alfalfa field located within approximately 114 m distance from a cotton field acted as a source of *L. hesperus* in the Arizona cotton agroecosystem. They found a strong positive correlation between *L. hesperus* abundance in alfalfa and a *L. hesperus* population in nearby cotton. Large populations can develop in an alfalfa field and eventually may move from alfalfa to cotton, especially when alfalfa is harvested (Graham, Jackson & Debolt, 1986). While this phenomenon has been reported, it has never been specifically quantified and characterized. MRR study detected "unidirectional" movement of marked insects from the point of release to the point of sampling. FMMC study allowed us to mark and recapture a large number of *L. hesperus* in field settings. The results obtained from MRR and FMMC did not provide a complete picture of intercrop movement of *L. hesperus*; however, they provided strong evidence confirming the effectiveness of the marking and detection technique. A detailed study of bidirectional *L. hesperus* intercrop movement between alfalfa and cotton in natural field settings will increase our understanding of the cotton-alfalfa source-sink relationships.

Insect intercrop movement behavior is a complex phenomenon affected by biological and ecological factors and dependent upon both the insect and the host habitat. Quantification of insect movement is necessary in developing a model determining insect dispersion and insect intercrop movement. Field-marking using protein markers and subsequent marker detection via indirect ELISA is a potential method for temporal and directional insect intercrop movement quantification. This technique proved superior to traditional surveying techniques in elucidating *L. hesperus* source-sink dynamics in a cotton-alfalfa system. A key limitation of this approach is difficulty in predicting actual insect pest population changes in a field crop due to the process of bidirectional intercrop movement. As an example, higher net insect pest intercrop movement does not necessarily equate to increased damage in the affected host crop. Further studies involving this technique should examine the effect of *L. hesperus* intercrop movement on *L. hesperus* reproductive success in cotton and resulting cotton crop damage (Chen & Parajulee, 2010). Because insect intercrop movement can be influenced by environmental factors, host quality, and crop management practices, a mathematical model, derived from detailed evaluation of these factors, should be developed to predict insect pest intercrop movement behavior. Such a model could then be integrated with the tools available to growers and researchers for ecologically intensive pest management in cotton.

Acknowledgments

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RESEARCH ARTICLE

Dynamic Optimization of Nitrogen in Plateau Cotton Yield Functions with Nitrogen Carryover Considerations

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Abstract
This study utilizes a dynamic programming decision model, considering an intertemporal nitrogen carryover function, combined with both linear stochastic and deterministic plateau response functions to evaluate optimal nitrogen fertilizer decision rules and net present values (NPVs) in Texas High Plains cotton production. Nitrogen recommendations and NPVs are influenced by response function choice and nitrogen-to-cotton price ratios. Results indicate the stochastic plateau function better describes the data; the optimum nitrogen recommendation is to apply approximately 40 lb. of nitrogen for each bale of cotton production when considering nitrogen carryover information.

Keywords: Carryover; cotton production; nitrogen optimization; plateau; Texas High Plains

JEL Classifications: Q10; Q24

1. Introduction

The Southern High Plains region of Texas (SHPT) is one of the most cotton-intensive production areas in the world. Producers in this region face challenges related to increasing input costs, volatile seed and lint prices, and limited productivity given water constraints (Parajulee and Shrestha, 2014). Irrigation water and nitrogen fertilizer are two common limiting input factors in SHPT cotton production. Declining Ogallala aquifer volume has contributed to increased proportions of dryland cotton acreage during the last 10 years (U.S. Department of Agriculture, National Agricultural Statistics Service, 2018). Additionally, cotton farmers are challenged by increasing nitrogen fertilizer prices (Bronson et al., 2006). Moreover, nitrogen is one of the most expensive inputs, accounting for 15% to 20% of cotton production costs (Smith, 2016).

Economically, optimal fertilizer rates can be obtained by maximizing expected net revenues subject to crop yield functions. The fitting of crop yield response functions to yield data has become an increasingly common method among economists to derive economic profitability models in agricultural crop production systems (Tembo et al., 2008).

Of all the functional forms developed on theoretical and empirical grounds, polynomial functions are most commonly used (Frank, Beattie, and Embleton, 1990; Harper et al., 2012; Heady and Dillon, 1961; Hurley, Oishi, and Malzer, 2005; Roberts, English, and Larson, 2006; Xu et al., 2009). This functional form is assumed to be linear in parameters with no plateau growth and often overestimates maximum yield and optimal fertilizer recommendation (Ackello-Ogutu, Paris, and Williams, 1985; Lanzer and Paris, 1981). The linear response plateau (LRP) model, proposed by Cate and Nelson (1971), has become popular in recent years. This functional form is based on the agronomic principle of "law of minimum" formulated by Von Liebig (1855), per which crop growth is governed by the most limiting ("minimum") factor until another factor becomes limiting. The constant yield with an additional input represents the yield potential of the crop, also referred to as the plateau yield. The point where the plateau begins corresponds to the optimal input. Contrary to polynomial response forms, the LRP model does not allow for nutrient substitution and implies a sharp transition to a plateau maximum.

Past studies have argued that LRP models explained crop response to fertilizers at least as well as polynomial forms, if not better (Ackello-Ogutu, Paris, and Williams, 1985; Anderson and Nelson, 1975; Babcock and Blackmer, 1994; Grimm, Paris, and Williams, 1987; Lanzer and Paris, 1981; Paris, 1992; Perrin, 1976; Waugh, Cate, and Nelson, 1973). However, plateau response functions have often assumed that inputs are perfectly controllable, and plateau is deterministic (Cox, 1996; Llewelyn and Featherstone, 1997; Paris and Knapp, 1989). In reality, agricultural inputs are not fully controlled and are often hard to quantify (Sher and Amir, 1994), and crop response to inputs can vary with years and field locations (Cerrato and Blackmer, 1990). Further, the nonrandom plateau function does not consider potential interaction between the primary input (nitrogen) and environmental factors when modeling crop yield response (Boyer et al., 2015). With the increasing criticism of the deterministic plateau, focus shifted to stochastic plateau functional forms. Makowski and Wallach (2002) considered the stochastic plateau, and Berck and Helfand (1990) examined randomness in plateau. Raun et al. (2002) considered randomness of inputs, plateau, and intercept but did not consider random effects. Paris (1992) found a switching regression model supported the Von Liebig hypothesis.

Recently, Tembo et al. (2008) modified the LRP by including uncorrelated random effects that shifted both the intercept and plateau, which allowed them to be stochastic, and developed the linear response stochastic plateau (LRSP) functional form. The LRSP functional form includes two independent random effects: year random effects and plateau year random effects. The year random effect acts as an intercept, and the plateau year random effect allows year-to-year variation of expected yield potential. The study also developed a direct formula to estimate optimal fertilizer rates that maximize expected returns. The LRSP function has been used extensively to model crop yields to fertilizers in cotton, wheat, forage, corn, potatoes, and sorghum (Asci, Borisova, and VanSickle, 2015; Biermacher et al., 2009; Boyer et al., 2013, 2015; Brorsen and Richter, 2012; Harmon et al., 2016; Kaitibie et al., 2003, 2007; Tumusiime et al., 2011; Zhou et al., 2015).

Although both deterministic- and stochastic-plateau–type models have been popularly utilized with large degrees of predictability in many production situations, these models could have an additional random effect on the response portion and might result in suboptimal fertilizer decision rules for the single-year planning model because of the dynamic nature of fertilizer in soil. Crops acquire nitrogen from two sources: applied nitrogen in the current crop production year and carryover nitrogen from previous years (Lemon et al., 2009). Further, carryover nitrogen at a given time depends on previous nitrogen application and prior levels of residual nitrogen. Without accounting for carryover information in a dynamic model, these plateau-type models may not optimize production efficiency and environmental sustainability in the long run. Consideration of carryover nitrogen prior to nitrogen application changes the producer's decision framework from maximizing expected profit in a given year to maximizing the net present value (NPV) of net returns over a planning horizon. This is because application levels in a given year are based on their application rates from the previous year. Given this, many Texas High Plains cotton producers use soil test data to adjust year-to-year nitrogen application regimes.

Studies have shown that accumulation of carryover fertilizers significantly affects crop yield and net revenue in succeeding years (Harmon et al., 2016; Harper et al., 2012; Jomini et al., 1991; Raun et al., 1998; Segarra et al., 1989). However, the degree of nitrogen accumulation varies with the soil environment (e.g., rainfall) and soil health (e.g., available soil microbes, cation exchange, and organic matter). It may be noted that geographic variation influences nitrogen carryover effects. In arid regions with dry soil, nitrogen uptake is often less than that seen in higher rainfall areas. This increases the likelihood that residual nitrogen will be left in the soil (Huang, Lu, and Uri, 2001). Thus, it can be speculated that the degree of nitrogen carryover is likely greater in a low-rainfall area such as the Texas High Plains. Soil nitrogen testing provides carryover information to assist producers in improving the application of nitrogen fertilizer, including determination of whether nitrogen fertilizer is needed, and avoidance of excess nitrogen fertilizer use, which reduces fertilizer costs.

Fertilizer carryover effects were discussed previously by Heady and Dillon (1961), Fuller (1965), Anderson (1967), Kennedy et al. (1973), Godden and Helyar (1980), and Kennedy (1981). These studies resulted in the derivation of the optimality condition for fertilizer application with carryover effects using a dynamic optimization approach. However, most classical dynamic programming models have assumed either polynomial or deterministic plateau yield response functional forms (Harper et al., 2012).

Economic literature on simultaneous use of plateau yield function and dynamic optimization of fertilizers using carryover information is limited. Recent work by Harmon et al. (2016, 2017) determined the value of soil test information for potassium in upland cotton production utilizing plateau functions; however, studies using the stochastic plateau model, while considering carryover effects, in nitrogen management decisions are scarce. Thus, this article utilizes stochastic and plateau functions to consider changes in nitrogen fertilizer recommendation levels, when considering carryover, with respect to nitrogen-to-cotton price ratios. Using a stochastic plateau crop yield function in a dynamic programming approach could improve nitrogen fertilizer recommendation levels and offer more efficient cotton production.

In this study, we combine stochastic and nonstochastic plateau functions in a deterministic dynamic optimization model, which considers an intertemporal nitrate nitrogen residual function. We examine optimal nitrogen rates, which maximize expected yield, expected profits, and NPV of returns using stochastic and deterministic plateau functions considering carryover nitrogen. This allows us to examine the value of using a stochastic plateau function over its deterministic counterpart, while incorporating nitrogen carryover information under different input-output price scenarios. Specifically, this research uses Tembo et al.'s (2008) stochastic plateau yield function with Kennedy's (1986, 1988) dynamic programming model to make methodological contributions in the estimation of optimal input decision rules in production economics.

2. Experimental design and data

A long-term field experiment was conducted on a 5-acre, subsurface drip-irrigated field at the Texas A&M AgriLife Research farm near Plainview, Texas (34.147 N, −101.947 W). Five nitrogen application rates (0, 50, 100, 150, and 200 lb./acre) were applied to the same experimental units consistently for 14 consecutive years from 2002 to 2015. The experiment consisted of a randomized block design with five treatments and five replications. Residual soil nitrogen was monitored annually before applying nitrogen treatment, by taking two 24-inch core samples from each plot. Samples were sent to Ward Laboratories in Kearney, Nebraska, for analysis. Regionally well-adapted commercial cotton cultivars were used over the duration of this study, including PM2379RR (2002, 2003, 2004, and 2005), FM960B2R (2006, 2007, 2008, 2009, and 2010), DP104B2RF (2011), FM9063B2RF (2012, 2013, and 2014), and FM9180B2F (2015). Change in cultivars over the study duration was necessitated because of new cultivar development and discontinuation of older cultivars. Average lint yield from each plot was calculated in pounds per acre for each year.

Analysis of variance (ANOVA) for yield and net returns by applied nitrogen with pairwise comparison based on the least significant difference is shown in Table 1. These results indicate that zero-applied nitrogen (i.e., plots that received no nitrogen augmentation) produced the lowest yield, and yield increased linearly with nitrogen augmentation until the highest yield occurred

Table 1. Least square means of cotton lint yield and net return above nitrogen cost, 2002–2015

Applied Nitrogen (lb./acre)	Carryover Nitrogen (lb./acre)	Yield (lb./acre)	Gross Revenue[a,b] ($/acre)	Net Returns[a,c] ($/acre)
0	23.28 (17.94)	908.64 C (308.47)	590.61 C (200.50)	590.61 (200.50)
50	28 (20.49)	1,112.73 B (373.91)	723.27 B (243.04)	698.27 (243.04)
100	45.92 (58.35)	1,208.64 AB (414.77)	785.62 AB (269.60)	735.62 (269.60)
150	40.32 (26.46)	1,270.43 A (488.91)	825.78 A (317.79)	750.78 (317.79)
200	66.07 (61.56)	1,270.25 A (481.32)	825.67 A (312.86)	725.67 (312.86)

[a]The selected prices are $0.50/lb. and $0.65/lb. for nitrogen and cotton, respectively.
[b]Gross Revenue = Yield × $0.65/lb.
[c]Net Returns = Gross Revenue − (Applied Nitrogen × $0.50/lb.).
Note: Values in the same column and with the same uppercase letters are not significantly different, and figures in parentheses indicate standard deviation.

with 150 lb./acre of applied nitrogen. The yield achieved with a nitrogen application rate of 150 lb./acre was significantly higher than that with zero and 50 lb./acre of applied nitrogen but was not significantly different from 100 and 200 lb./acre of applied nitrogen. The results imply that optimum applied nitrogen lies somewhere between 50 and 150 lb./acre of applied nitrogen. The weakness of ANOVA is that only discrete choices are considered, so the single optimum point within the given ranges cannot be identified.

Prices of nitrogen and lint cotton (in dollars per pound) used in this study were acquired from Texas A&M AgriLife Extension Service budgets prepared for the South Plains District of Texas (Smith, 2016). Five sets of lint and nitrogen prices were used to estimate the different levels of return streams via NPV analysis. Ten-year average prices were taken as a reference, $0.65/lb. and $0.50/lb. for lint and nitrogen, respectively, and four additional price sets corresponding to 20% and 40% below and above the average prices. Thus, the five price scenarios for lint and nitrogen prices per pound, respectively, were $0.39 and $0.30, $0.52 and $0.40, $0.65 and $0.50, $0.78 and $0.60 and $0.91 and $0.70. A 10-year planning horizon and a 35-lb./acre initial condition of residual nitrate nitrogen were also considered. Further, a 5% discount rate was applied to represent the opportunity cost of land in cotton production, as per previous studies (Harper et al., 2012).

Normal data are an underlying assumption for maximum likelihood estimation, so assessment for normality of residuals is a prerequisite. Tests for normality of residuals were applied using both graphic and numeric methods. Results showed that both the Kolmogorov-Smirnov test and the Cramer–von Mises test were not significant ($P = 0.18$, $P = 0.16$); thus, there is evidence that the residuals follow the normal distribution. A simple linear model was run over the study period and showed a yield trend slope of −7.24 with a standard error of 6.06. That is, the Student *t*-test results did not show a significant time trend, so time trend was not considered when modeling cotton yield response. Other studies have found considerable genetic improvement in cotton using GMO (genetically modified organism) varieties (Ouedraogo, Brorsen, and Arnall, 2016); however, we find no similar trend over time, likely because of the use of non-GMO varieties in this study.

3. Conceptual and empirical models

In the present study, nitrogen is considered a limiting factor so that augmentation of nitrogen leads to a linear increment in cotton yield. Under the concept of zero elasticity of substitution for all levels of nitrogen, the Von Liebig hypothesis of "law of minimum" infers the notion of plateau (Anderson and Nelson, 1975; Lanzer and Paris, 1981; Paris, 1992; Perrin, 1976). The notion of plateau implies that a cotton crop responds to a supply of nitrogen at a constant slope until maximum potential yield (plateau) is reached. Once the plateau is reached, nitrogen will no longer be a limiting factor, and an additional unit of nitrogen suggests wastage of the input and economic burden to producers. The relationship between nitrogen application and the attainment of plateau is illustrated in Tembo et al. (2008).

3.1. Linear response plateau function

Using LRP functional form, the lint yield response to nitrogen can be expressed as follows:

$$y_{it} = min(\beta_0 + \beta_1 NT_{it},\ \mu) + \tau_t + \epsilon_{it}, \tag{1}$$

where y_{it} is lint yield (pounds per acre) from plot i in period t, β_0 is response at the origin, β_1 is the linear slope parameter for nitrogen, NT_{it} is total nitrogen from plot i in period t, μ is the plateau, $\tau_t \sim N\left(0,\ \sigma_\tau^2\right)$ is an intercept year random effect, and $\epsilon_{it} \sim N\left(0,\ \sigma_\epsilon^2\right)$ is a random disturbance term. Both error terms are assumed to be i.i.d. (independent and identically distributed), and total variance $\left(\sigma_T^2\right) = \sigma_\epsilon^2 + \sigma_\tau^2$.

The function is continuous, but derivatives do not exist with respect to NT at the knot point where the linear response and plateau are joined (Park et al., 2007). The optimal level of nitrogen (NT_{it}^*) can be determined based on equation (1). A nonstochastic LRP function will show constant positive marginal value product (MVP) when $\beta_0 + \beta_1 NT_{it} < \mu$, and nitrogen should be applied until MVP ($P_t\beta_1$, where P_t is the price of lint [dollars per pound] in year t) equals marginal fixed cost minus the value of fertilizer savings in the current year, because of carryover effects of the previous year's fertilizer application (k). Thus, the optimal nitrogen level for LRP would be either zero or the nitrogen level to reach the plateau (Boyer et al., 2013; Park et al., 2007; Tembo et al., 2008):

$$N = \begin{cases} NT* \ if\ p_t\beta_1 > k \\ 0\ otherwise \end{cases}, \tag{2}$$

$$NT* = \frac{\mu - \beta_0}{\beta_1}.$$

3.2. Linear response stochastic plateau function

Following Tembo et al. (2008), the LRSP to model lint yield response to nitrogen is

$$y_{it} = min(\beta_0 + \beta_1 NT_{it}, \mu + u_t) + \tau_t + \epsilon_{it}, \tag{3}$$

where $u_t \sim N(0, \sigma_u^2)$ is a plateau year random effect that enters nonlinearly, and other terms are as defined previously. Total nitrogen (NT_{it}) is used to model the yield function based on model selection criteria such as Akaike information criterion, Bayesian information criterion, and likelihood ratio test, rather than including both applied nitrogen (NA_{it}) and carryover nitrogen (NR_{it}). Three residual terms are assumed to be i.i.d., and total variance $\left(\sigma_T^2\right) = \sigma_u^2 + \sigma_\tau^2 + \sigma_e^2$.

Based on the censored normal distribution theorem developed for Tobit models and applying chain rules, one can derive the optimal total nitrogen level as developed by Tembo et al. (2008, p. 427):

$$NT_{it}^* = \frac{1}{\beta_1}(\phi^{-1}\sigma_u^2 - \beta_0 + \mu), \tag{4}$$

where $\Phi^{-1} = \Phi^{-1}(1 - \frac{k}{p_t\beta_1})$ is the inverse of the standard normal cumulative distribution function assuming ($\beta_1 \geq \frac{k}{p_t}$); otherwise zero nitrogen would be optimal. Alternatively, it can be expressed as follows:

$$NT_{it}^{*} = \frac{1}{\beta_1}(\mu + Z_{\alpha}\sigma_u - \beta_0), \tag{5}$$

where $Z_{\alpha} = [\frac{\beta_0 + \beta_1(NT_{it}) - \mu}{\sigma_u}]$ is the standard normal variate with $\alpha = 1 - \emptyset = \frac{k}{p_t \beta_1}$, and the expected profit-maximizing yield is calculated by Tembo et al. (2008) as

$$E(y_{it}) = (1 - \Phi)a + \Phi\left(\mu - \frac{\sigma_u \phi}{\Phi}\right), \tag{6}$$

where $a = \beta_0 + \beta_1 NT_{it}$, $\Phi = \Phi[\frac{a-\mu}{\sigma_u}] = prob(\mu \leq a)$ is the cumulative normal distribution function and $\phi = \phi[\frac{a-\mu}{\sigma_u}]$ is the standard normal density function. Maximum likelihood parameter estimates for equations (1) and (3) were obtained using the NLMIXED procedure in SAS 9.4 (Brorsen and Ouedraogo, 2015; SAS Institute Inc., 2016).

In the case of symmetric distribution, which occurs when $k/(p\beta_1)$ equals 0.5, the optimum level of nitrogen for the nonstochastic plateau model would be equal to that for the stochastic plateau model (Tembo et al., 2008). When the distribution is symmetric and $k/(p\beta_1) < 0.5$, the optimal level of nitrogen under the stochastic plateau model is higher than with a nonstochastic model if all other parameters are the same.

3.3. Carryover function

The linear carryover function is a commonly used functional form (Harper et al., 2012; Park et al., 2007), where carryover nitrogen in the next production year is linearly proportional to the total available nitrogen in the soil in the current year. The nitrogen carryover function used here is a linear function of total available nitrogen adapted from Kennedy (1986) and used by Segarra et al. (1989) for nitrogen in cotton production. Further, we assume that applied and residual nitrogen levels have different effects on the amount of nitrogen being carried over to the next period because of soil nitrate-nitrogen dynamics. The linear carryover function is given by

$$NR_{it+1} = \alpha_o + \alpha_1 NA_{it} + \alpha_2 NR_{it} + \tau_t + \varepsilon_{it+1}, \tag{7}$$

where α_1 and α_2 are parameters; NA_{it} and NR_{it} are the amounts of applied and carryover nitrogen from plot i in period t, respectively; $\tau_t \sim N(0, \sigma_t^2)$ is an intercept year random effect that captures the year-to-year variation of residual nitrogen in soil; and $\epsilon_{t+1} \sim N(0, \sigma_{\epsilon}^2)$ is a random disturbance term. Both error terms are assumed to be i.i.d.

3.4. Dynamic programming approach

A risk neutral, profit-maximizing cotton producer can choose an amount of nitrogen fertilizer (NA_t) to be applied for each production year (t), ($t + 1 \ldots T$) with carryover nitrate nitrogen (NR_t), which maximizes the NPV of a stream of returns over a planning horizon (Kennedy, 1986; Kennedy et al., 1973). The optimality condition of this scenario can be expressed as follows:

$$\underset{NA_t}{MAX}\, NPV = \sum_{t=1}^{T} \delta^t [P_t \times Y_{it}(NT_{it}) - C_t \times NA_{it}], \tag{8}$$

$$\text{subject to } NT_{it} = NA_{it} + NR_{it}, \tag{9}$$

$$NR_{it+1} = \alpha NT_{it}, \tag{10}$$

$$NA_{it}, NR_{it}, NT_{it} \geq 0, \tag{11}$$

with NR_1 is given:

$$NR_{iT+1} = 0, \tag{12}$$

$$NR_0 = NR(0), \tag{13}$$

where NPV is the per acre present value of returns (in dollars); T is the length of the decision-maker's planning horizon in years; NT_{it}, P_t, and C_t are defined previously; $Y_{it}(NT_{it})$ is the cotton yield function (pounds per acre) in year t; $\delta = (1 + r)^{-1}$ is the discount factor, where r is the discount rate reflecting the producer's opportunity cost of time; and α is the carryover coefficient ($0 \leq \alpha \leq 1$), which is a proportion of available nitrogen fertilizer in period $t + 1$ that is carried over from nitrogen application in period t. The decision variable is $NA_{it,}$ the amount of nitrogen to be applied in each crop season. The static variable is residual NR_{it} remaining in the soil before planting next year's cotton. Fixed costs were ignored because they do not affect the determination of the optimal amount of nitrogen to apply. Equation (8) was estimated using the general algebraic modeling system (Segarra et al., 1989).

The optimal amount of nitrogen (NA*) to apply each year can be solved using a recursive functional equation (Bellman, 1957), which is given by

$$F_t\{NR_{it}\} = \max_{NA_{it}}\{\delta P_t Y_{it}\left(NA_{it}^* + NR_{it}\right) - C_t \times NA_{it}^* + \delta F_{t+1}\left[\alpha\left(NA_{it}^* + NR_{it}\right)\right]\}, \tag{14}$$

with $F_{T+1}\{NT_{iT+1}\} = 0$, as a terminal condition, where $F_t\{NR_{it}\}$ is the present value of net returns (dollars per pound) from optimal nitrogen application (NA_{it}^*) in each year of the period t considering nitrogen carryover NR_{it}, NA_{it} is the amount of nitrogen applied from plot i in year t, $\delta = (1 + r)^{-1}$ is the discount factor, P_t is the price of lint (dollars per pound) in year t, C_t is the cost of nitrogen (dollars per pound) in year t, Y_{it} represents cotton yield (pounds per acre) from plot i in year t, α is a carryover parameter ($0 \leq \alpha \leq 1$), and the proportion of fertilizer available in period t ($NR_{it} + NA_{it}$) carried over to period $t + 1$.

The envelope theorem (Leonard and van Long, 1992) is applied to estimate the value of carryover fertilizers to subsequent years. Differentiating equation (14) with respect to NA_{it} gives the first-order necessary condition for an interior maximum, which is as follows:

$$\frac{\partial F_t}{\partial NA_{it}} = \delta P_t \frac{\partial Y_{it}}{\partial NA_{it}} - C_t + \delta\alpha \frac{\partial F_{t+1}}{\partial NR_{it+1}} = 0. \tag{15}$$

Again, differentiating equation (14) with respect to NR_t, the first-order condition for net return maximization (Harper et al., 2012) is as follows:

$$\frac{\partial F_t}{\partial NR_{it}} = \delta_t P_t \frac{\partial Y_{it}}{\partial NA_{it}} + \delta\alpha \frac{\partial F_{t+1}}{\partial NR_{it+1}} = 0. \tag{16}$$

Because this is a linear term, the marginal responses to total, applied, and carryover nitrogen are identical (Kennedy, 1986), and we see that

$$\frac{\partial NT_{it}}{\partial NA_{it}} = \frac{\partial NT_{it}}{\partial NR_{it}} = 1, \text{and} \tag{17}$$

$$\frac{\partial Y_{it}}{\partial NT_{it}} = \frac{\partial Y_{it}}{\partial NA_{it}} = \frac{\partial Y_{it}}{\partial NR_{it}}; \left(\text{by chain rule}\right), \text{we get}, \frac{\partial NR_{it+1}}{\partial NA_{it}} = \alpha. \tag{18}$$

From equations (15), (16), and (17), this can be written as

$$\frac{\partial F_t}{\partial NR_{it}} = C_t, \tag{19}$$

which implies that the value of an additional unit of nitrogen fertilizer being carried over from the previous year to the current year should be equal to the per unit cost of nitrogen in the current year, irrespective of the amount being carried over.

Updating $\frac{\partial F_t}{\partial NR_{it}}$ for a single period $t + 1$ and from equations (16) and (18), we get

$$\delta P_t \frac{\partial Y_t}{\partial NT_{it}} = C_t - \delta\alpha C_{t+1} = k. \tag{20}$$

For the sake of convenience, we assume $C_t - \delta_t \alpha C_{t+1}$ to be k, which states that the present MVP of fertilizer should be equal to the opportunity cost of the marginal unit of nitrogen fertilizer to achieve the optimality condition. If a cotton farmer does not consider nitrogen carryover, then $NR_t = 0$ and the optimal condition for a single-period nitrogen application becomes

$$\delta P_t \frac{\partial Y_t}{\partial NT_t} = C_t. \tag{21}$$

This suggests that the single-year planning model yields suboptimal or inefficient levels of nitrogen application, and the discounted nitrogen fertilizer savings remain in the soil until the period is no longer considered. Further, Tembo et al. (2008, p. 426) showed

$$\frac{\partial Y_t}{\partial NT_t} = \beta_1(1 - \Phi), \tag{22}$$

where $\Phi = \Phi[\frac{\beta_0 + \beta_1 NT_t - \mu}{\sigma_u}]$ is a standard normal cumulative distribution function and $0 \leq \phi \leq 1$.

Substituting equation (21) into equation (20) produces the optimality condition as

$$\delta_t P_t \beta_1(1 - \Phi) = k. \tag{23}$$

These savings ($\delta\alpha C_{t+1}$), which are the discounted savings from nitrogen fertilizer carried over to the next year, were subtracted from the price because fertilizer carryover reduces the amount of applied fertilizers needed in the following years. Equation (23) states that for the optimality condition ($NA_t = NA_t^*$), the profit-maximizing condition occurs when the present value of the current crop and input savings from future fertilizer equal the expected fertilizer cost in subsequent years. The general rule of dynamic optimization is that fertilizer be applied up to the level where the expected present value of returns from the current year crop and future fertilizer application savings obtained from the marginal unit of fertilizer equal the current fertilizer cost (Kennedy, 1986).

3.5. Yield response function estimation

The models were constructed using the PROC NLMIXED procedure in SAS using maximum likelihood estimation methods. The NLMIXED procedure maximizes the marginal log-likelihood functions, directly using the theory of nonlinear mixed effects models (Wolfinger, 1999).

The random disturbance term and intercept year random effect enter the functions linearly, whereas the plateau year random effect enters nonlinearly, which does not have a closed form solution and can only be approximated numerically. The most common problem associated with nonlinear optimization is obtaining convergence, and the optimization algorithm may converge to a local instead of a global optimum (SAS Institute Inc., 2013). To address this, first-order approximation was used to obtain starting values, and various combinations of starting values were then used as the starting points in nonadaptive, 31-point Gaussian quadrature, which is much less likely to fail to converge or converge to a local optimum (Brorsen and Richter, 2012). The Newton-Raphson optimization algorithm was used to carry out the maximization.

4. Results

4.1. Parameter estimates

Parameter estimates for cotton lint yield response to total nitrogen, using both functional forms, are reported in Table 2. All parameters and variance components were significantly different from

Table 2. Cotton yield response to nitrogen with stochastic and deterministic plateau functions

	Stochastic Plateau		Deterministic Plateau	
Parameter	Estimate	Standard Error	Estimate	Standard Error
Intercept (β_0)	817.12***	72.88	819.74***	84.75
Slope of nitrogen (β_0)[a]	3.94***	0.68	3.90***	0.68
Plateau yield (μ) (lb./acre)	1,225***	80.17	1,226***	77.37
Plateau random effect (σ_u^2)[b]	31,711***	16.36	-	-
Intercept random effect (σ_v^2)[b]	55,247***	4.59	80,235***	6.44
Random disturbance (σ_e^2)	43,123***	3,512.71	50,358***	4,027.19
Plateau nitrogen (lb./acre)	104***	16.85	105***	11.78
Covariance (σ_u^2, σ_v^2)	75.12		-	
Akaike information criterion	4,507.60		4,536.40	
Bayesian information criterion	4,511.40		4,539.60	
−2 Log likelihood	4,495.60		4,526.40	
Observations	377			

[a]Slope of nitrogen is for total nitrogen.
[b]Random effects are for year.
Note: Asterisks (*, **, and ***) indicate $P < 0.10$, $P < 0.05$, and $P < 0.01$, respectively (two-tailed test).
Source: Data from Texas A&M AgriLife Research farm near Plainview, Texas, 2002–2015.

zero at the 1% level, based on Wald *t*-tests. The plateau random effect was significant with the LRSP model, indicating that the plateau is stochastic.

Goodness of fit for both stochastic and deterministic plateau functions was evaluated using the likelihood ratio test with 1 degree of freedom. The calculated likelihood ratio test statistic was 30.8 with a critical chi-square value of 6.63, providing evidence that the stochastic plateau model fit the cotton yield data relatively better than its deterministic counterpart. These results agreed with previous studies (Boyer et al. 2012, 2013; Harmon et al. 2016; Kaitibie et al., 2007).

The expected plateaus of cotton lint yield were 1,226 lb./acre and 1,225 lb./acre for LRP and LRSP functions, respectively. The estimated marginal productivity of total nitrogen was slightly higher with the LRSP model (3.94) than with LRP (3.90), so less nitrogen was needed to reach the plateau. Tembo et al. (2008) and Tumusiime et al. (2011) emphasized attenuation bias to explain the lower estimates of nitrogen productivity with the deterministic plateau model. The MVP of nitrogen with the LRSP model, when the price of cotton was \$0.65, was \$2.56/lb. Further, the threshold level of total nitrogen required to achieve a plateau knot was slightly higher for LRP (105 lb./acre) than that for LRSP (104 lb./acre).

4.2. Nitrate nitrogen carryover function

The nitrate nitrogen carryover function describes the rates at which both applied nitrogen and nitrate nitrogen, residual available in the soil from previous years, become available to the current year's crop. The nitrogen carryover function is estimated via the linear mixed effects model using maximum likelihood estimation as shown in Table 3.

Positive signs for an intercept and lag of applied and residual nitrogen were expected in the nitrogen carryover function. Both applied and residual nitrogen variables were used in carryover

Table 3. Soil nitrogen carryover function parameter estimates

Parameter	Estimate	Standard Error
Intercept (α_0) (lb./acre)	15.95***	4.99
Slope of lag applied nitrogen (α_1) (lb./acre)	0.06**	0.03
Slope of lag residual nitrogen (α_2) (lb./acre)	0.47***	0.05
Intercept random effect (σ^2_{v-1})[a]	219.20**	112.90
Random disturbance (σ^2_e)	908.06***	73.27
−2 Log likelihood	3,174.10	
Likelihood ratio test	19.97***	
Observations	377	

[a]Random effects are for year.
Note: Asterisks (*, **, and ***) indicate $P < 0.10$, $P < 0.05$, and $P < 0.01$, respectively (two-tailed test).
Source: Data from Texas A&M AgriLife Research farm near Plainview, Texas, 2002–2015.

functions (variance inflation factor was 1.12, indicating no evidence of multicollinearity).[1] All parameters were significantly different from zero at any conventional confidence level, except for applied nitrogen, which was significant at the 5% significance level. The estimated intercept implies that nearly 16 lb./acre of nitrogen was added each year in soil, as plant-available nitrogen may become accessible through natural phenomena such as the decay and breakdown of organic matter, weathering of soil particles, nitrogen fixation by leguminous weedy plants between two cropping seasons, and so forth. Different carryover coefficients for applied and residual nitrogen were observed. The estimated carryover coefficient for applied nitrogen was 0.06, which indicated that for each 100 lb./acre of applied nitrogen, soil nitrogen (in the form of nitrate nitrogen) increased by 6 lb./acre the following year. Thus, 6% of the previous year's total applied nitrogen carried over to the current year as residual nitrate nitrogen. Interestingly, the carryover coefficient for residual nitrogen indicated that nearly 47% of residual nitrogen was not used by the plant and carried over to the following period. This result indicates that nitrogen form, applied versus residual, affects carryover amounts differently. This finding is in line with Stoecker and Onken (1989), who showed that the effect of residual soil nitrogen on cotton yield was significantly different from that of applied nitrogen. We speculate that residual nitrate nitrogen is more stable in the soil profile, and less vulnerable to nitrogen losses, than nitrogen augmented in the soil in the current year. Because amounts of nitrate nitrogen in soil are affected by nitrogen application timing, form of nitrogen applied, rate of application, and amount of irrigation and rainfall, it is not surprising that the carryover coefficient of a more stable residual nitrogen is greater than the edaphically vulnerable applied nitrogen in our study. Using the likelihood ratio test, the null hypothesis of lack of random effects was rejected (likelihood statistics: 19.97 and $\chi^2_{1,0.05} = 3.84$).

4.3. Optimal nitrogen application rules

The optimal nitrogen level for deterministic plateau was either 104 lb./acre when the price of nitrogen was less than the sum of MVP ($2.53/lb.) of nitrogen and the value of fertilizer savings in the following year (because of carryover effect), or zero otherwise. Unlike the nonstochastic plateau, optimal nitrogen levels vary for the stochastic plateau given nitrogen-to-cotton price ratios and variance of plateau. Table 4 shows optimal nitrogen levels and corresponding expected

[1]For the sake of convenience, we used total nitrogen (applied nitrogen plus carryover nitrogen) to fit the residual nitrogen as a carryover function in the dynamic optimization approach. We found the carryover coefficient for total nitrogen to be 0.21 with a standard error of 0.02.

Table 4. Profit-maximizing total nitrogen, cotton yield, and recommended applied nitrogen scenarios with stochastic plateau function

	Cotton Price ($/lb.)				
Nitrogen Price ($/lb.)	$0.39	$0.52	$0.65	$0.78	$0.91
$0.30					
Profit-maximizing total N (lb./acre)	142	151	157	162	166
Profit-maximizing yield (lb./acre)	1,205	1,212	1,215	1,217	1,218
Recommended applied N (lb./acre)	101	109	115	119	123
$0.40					
Profit-maximizing N level (lb./acre)	133	142	149	155	159
Profit-maximizing yield (lb./acre)	1,197	1,205	1,210	1,214	1,216
Recommended applied N (lb./acre)	92	101	108	112	116
$0.50					
Profit-maximizing total N (lb./acre)	124	135	142	148	153
Profit-maximizing yield (lb./acre)	1,187	1,199	1,205	1,210	1,213
Recommended applied N (lb./acre)	85	95	101	106	110
$0.60					
Profit-maximizing total N (lb./acre)	116	128	136	142	147
Profit-maximizing yield (lb./acre)	1,176	1,192	1,200	1,205	1,209
Recommended applied N (lb./acre)	78	89	96	101	106
$0.70					
Profit-maximizing N level (lb./acre)	109	122	131	137	142
Profit-maximizing yield (lb./acre)	1,164	1,185	1,195	1,201	1,205
Recommended applied N (lb./acre)	71	83	91	97	101

Notes: Profit-maximizing yield corresponds to total nitrogen levels. Recommended level of nitrogen application is derived from per acre dynamic optimization of applied nitrogen with stochastic plateau function that maximizes the net present value over a 10-year planning period. This was calculated as profit-maximizing total nitrogen less a steady-state level of carryover nitrogen when considering soil test information.

maximum yield for 25 sets of cotton and nitrogen prices. The optimal level of total nitrogen ranged between 109 and 166 lb./acre when nitrogen-to-cotton price ratios ranged from 0.32 to 1.79. With the historical price scenarios, the total optimal nitrogen fertility was estimated to be 142 lb./acre. Once cotton yield response and carryover dynamics are known, a producer can determine the most profitable level of nitrogen to be applied in the current production year. For instance, a producer who considers carryover nitrogen information in nitrogen application decision rules can maintain the amount of nitrogen available for plant uptake by applying variable amounts annually.

Table 4 further depicts the expected profit-maximizing levels of nitrogen fertilizer application considering LRSP as the suitable functional form for 25 alternative cotton-nitrogen price scenarios. Dynamic optimization provides the optimal levels of nitrogen for augmentation, which is the difference between total nitrogen required to achieve plateau and residual nitrate nitrogen available in the soil because of carryover effects of the previous year's total nitrogen. The expected optimal nitrogen application, which maximized NPV, ranged from 71 lb./acre to 123 lb./acre depending on a given nitrogen-to-cotton price scenario. The lowest optimum nitrogen application level (i.e., 71 lb./acre) was obtained with a higher nitrogen-to-cotton price ratio (1.79) and

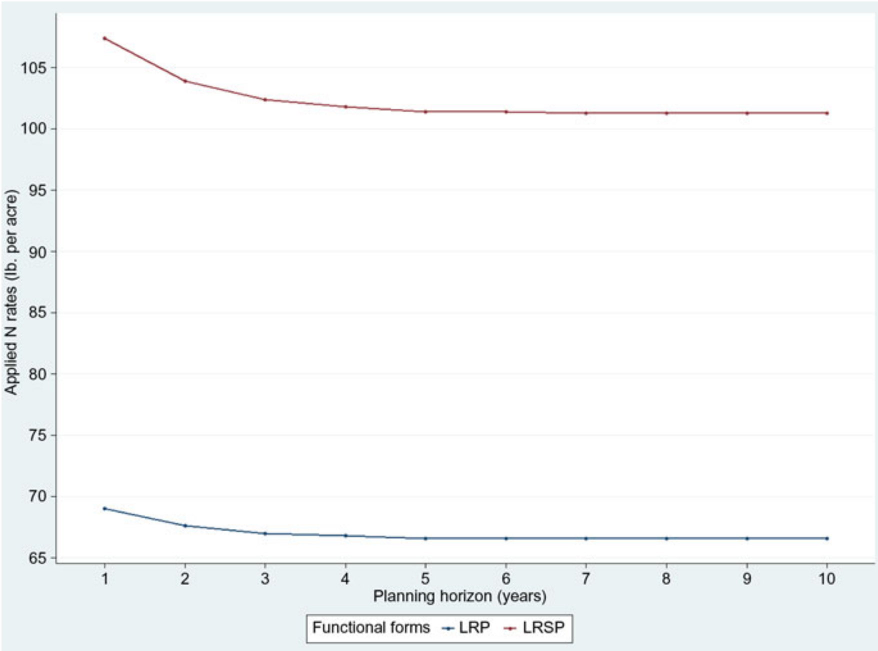

Figure 1. Steady-state optimal levels of applied nitrogen across periods with stochastic and deterministic plateau functions, assuming residual nitrogen of 35 lb./acre as a starting point.
Note: LRP, linear response plateau; LRSP, linear response stochastic plateau.

vice versa. Under the current input-output price combinations ($0.50 and $0.65), the steady-state optimum level of applied nitrogen was 101 lb./acre. Thus, 101 lb. of nitrogen applied in the current production year produced 2.54 bales of cotton.[2] As such, the optimum nitrogen recommendation is to apply approximately 40 lb. of nitrogen for each bale of cotton production. Bronson (2008) also showed that 40 lb. of total nitrogen was required to produce 1 bale of lint in West Texas, regardless of cotton variety or irrigation system. However, Hons et al. (2003) and Lemon et al. (2009) recommended 50 lb. of nitrogen per bale of cotton production from all sources. Nitrogen application decision rules should consider quantities of residual soil nitrogen, nitrogen in irrigation water, and plant-available nitrogen resulting from natural phenomena such as decay of organic matter. Contribution of nitrate nitrogen via irrigation water was unlikely at the study location; thus, differences in findings from this study and prior work are attributed to cultivar genetic performance.

Under a historical price scenario, the optimal levels of nitrogen were lower with deterministic plateau than with stochastic plateau because $c/(p\beta_1)$ was always less than 0.5, a condition generally used to compare the nitrogen requirement for profit maximization between stochastic and nonstochastic models. Under historical nitrogen-to-cotton price ratio scenarios (i.e., price ratios in the range of 0.5 to 1, if $\beta_1 > 2$), the LRP functional form underestimates the optimal nitrogen application levels for cotton production.

With dynamic optimization using parameter estimate yield functions, it is important to highlight that optimal nitrogen application levels vary across periods for a given nitrogen-to-cotton price ratio assuming a fixed amount of initial nitrogen residual. Figure 1 depicts optimal levels of applied nitrogen dynamics using LRP and LRSP functions over a 10-year planning period when nitrogen and cotton prices are $0.50 and $0.65/lb., respectively, and assuming a 35-lb./acre initial

[2]Average yield of cotton in our data was 2.54 bales/acre.

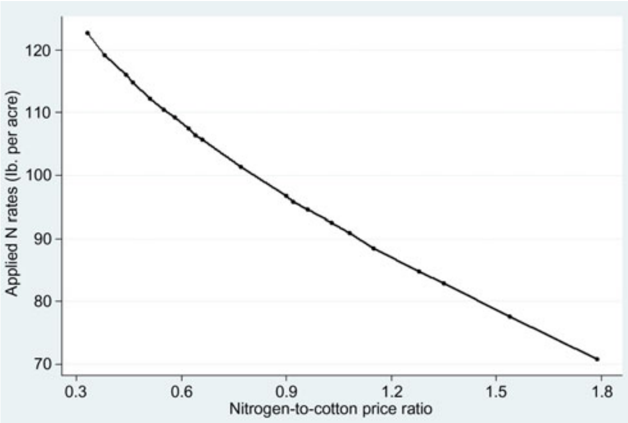

Figure 2. Relationship between applied nitrogen rates and nitrogen-to-cotton price ratios from the stochastic plateau function, assuming 35 lb./acre initial nitrogen residual.

nitrogen residual. Considering the LRP functional form, it shows that 69 lb./acre of applied nitrogen in the first year of the planning period is optimal, with application rate decreased until the steady-state optimal level of applied nitrogen, 67 lb./acre, is achieved, which is far below the current recommendation level. In contrast, when the LRSP functional form is assumed, given 35-lb./acre initial residual nitrogen, 107 lb./acre of applied nitrogen in the first year of the planning period would be optimal, with application rate decreased until a steady-state optimal nitrogen level of 101 lb./acre is reached.

The optimization model solves for specific input-output price combinations, but discrete combinations may vary substantially, so that a generalized relationship based on relative, rather than absolute, price scenarios could be more useful. Accordingly, a generalization of optimal nitrogen application levels was derived by regressing the optimal nitrogen application against the nitrogen-to-cotton price ratios. The 25 sets of optimal applied nitrogen levels along with their corresponding nitrogen-to-cotton price ratios are listed in Table 4. Figure 2 depicts the relationship between these optimal decision rules of nitrogen application and nitrogen-to-cotton price ratio. As expected, results indicate that the higher the nitrogen-to-cotton price ratio, the lower the optimal level of nitrogen applied.

The Texas A&M AgriLife Extension Service showed that the average nitrogen-to-cotton price ratio in the SHPT ranged from 0.5 to 1.0 between 2005 and 2015. At these historical price ratios, optimal nitrogen application levels lie in a range of 95 lb./acre to 112 lb./acre. Nevertheless, the current producer practice of nitrogen use in the SHPT is to apply 125 lb./acre regardless of prices, which is clearly much higher than any of these optimal application rates. This also suggests that if nitrogen-to-cotton price ratios remain close to the historical ratios, and if decision makers follow the nitrogen application optimal decision rules based on the LRSP model, cotton yield would be optimized and cotton production would be a more profitable enterprise. The optimal level of nitrogen application based on LRP models does not vary with nitrogen-to-cotton price ratios; rather, it remains constant until it satisfies the condition given in equation 2.

4.4. Net present values and valuation of carryover nitrogen

The empirical distributions of NPV for each of the 25 dynamic models, considering LRSP and LRP functional forms, are presented in Table 5. The benefit of using the LRSP model over the LRP model can be observed in the differences in expected NPV between these two models. Using LRSP functional form, substantially higher NPVs could be achieved. These increased NPVs ranged from $26 to $1,571/acre. Furthermore, if NPVs are evaluated at the average price combinations, the loss to producers from using LRP to predict optimal nitrogen application levels would

Table 5. Net present value (NPV) of returns from dynamic optimization of applied nitrogen using stochastic (LRSP) and deterministic (LRP) plateau functions

NPV of Returns ($/acre, 10-year planning horizon)										
Nitrogen Price($/lb.)	Cotton Price ($/lb.)									
	$0.39		$0.52		$0.65		$0.78		$0.91	
	LRSP	LRP	LRSP	LRP	LRSP	LRP	LRSP	LRP	LRSP	LRP
$0.30	3,911	3,543	5,414	4,776	6,941	6,009	8,486	7,241	10,046	8,475
$0.40	3,744	3,491	5,215	4,724	6,714	5,957	8,233	7,189	9,768	8,423
$0.50	3,601	3,440	5,044	4,672	6,519	5,905	8,016	7,138	9,529	8,371
$0.60	3,475	3,388	4,893	4,621	6,346	5,854	7,823	7,086	9,318	8,319
$0.70	3,362	3,336	4,757	4,569	6,189	5,802	7,648	7,034	9,127	8,267

Note: LRP, linear response plateau; LRSP, linear response stochastic plateau.

be $614/acre, projected over a 10-year time interval. Additionally, in order to calculate the value of carryover nitrogen, we considered a discount factor of 5% and carryover coefficient of 0.21; thus, the reduction in nitrogen price was found to be 20% (carryover coefficient, 0.21, divided by discount factor, 1.05) in the following period.

5. Conclusion

Currently available crop production models often combine either the dynamic programming approach with quadratic functions or stochastic plateau functions alone, without accounting for carryover nitrogen in fertilization problems. Selecting inappropriate functional forms or excluding substantial amounts of residual nitrogen from the model may result in imprecise as well as higher-on-average fertilizer recommendation. This research combines stochastic plateau functions with dynamic optimization techniques in order to develop optimal nitrogen decision rules. This article also examines the benefit of using a stochastic plateau function, in conjunction with carryover information, over a deterministic plateau. Specifically, this research combines Tembo et al.'s (2008) stochastic plateau yield function with Kennedy's (1986) dynamic programming model.

The results favor the stochastic plateau function, as it demonstrates a better fit to the data than its deterministic counterpart. Although there is a payoff to using the stochastic plateau function, the amount of payoff depends on the nitrogen-to-cotton price ratio. Unlike the deterministic plateau, profit-maximizing nitrogen level with the stochastic plateau is a function of the variance of plateau random effects and nitrogen-to-cotton price ratios. It should be noted that the LRP function may underestimate the profit-maximizing level of nitrogen under good growing conditions and may do the opposite under poor growing conditions. This result backs the finding of Tembo et al. (2008) who stated that "use of a stochastic plateau provides insight into why farmers may apply more or less nitrogen than would appear optimal" (p. 432).

It is important to note that the results derived in this study may be used with caution in other geographic areas because of the regional differences in climatic conditions, soil types, and production practices. Nevertheless, the approaches used in this study are applicable for the evaluation of crop production efficiency through optimal input application decision rules in other geographic locations and/or in other crop production systems.

The findings of this study are particularly important in light of escalating nitrogen prices, as well as the serious environmental challenge of managing nitrate contamination in groundwater. Moreover, this research considered the plateau year random effect because of year-to-year variation in yield plateau inflicted by environmental and weather conditions. Further research should include field plateau random effects to capture field-to-field variation of yield plateau for multiple field locations.

The results of this study provide useful insight into the value of nitrogen carryover information when using stochastic versus deterministic plateau functions. Reduction in nitrogen usage, based on carryover information, may help cotton farmers improve their profits, all else remaining constant. Additionally, negative environmental consequences resulting from the overapplication of nitrogen may be avoided.

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