

Article

Interactive Effect of Cover Crop, Irrigation Regime, and Crop Phenology on Thrips Population Dynamics and Plant Growth Parameters in Upland Cotton

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Abstract: Cotton (*Gossypium hirsutum*) requires a long growing period for fruit and fiber maturation, making it vulnerable to insect pests, thus affecting the seed cotton yield and fiber quality. Cotton-feeding thrips (Thysanoptera: Thripidae) are one of the major insects impacting cotton yield throughout the U.S. cotton belt and worldwide. A two-year field research conducted at Texas A&M AgriLife Research farm in west Texas, USA quantified the interactive effect of three cover crops [wheat (*Triticum aestivum*), rye (*Secale cereale*), and no cover] and three irrigation regimes [rainfed, deficit irrigation (30%) and full irrigation] on thrips population dynamics across the phenologically susceptible stages of upland cotton and resulting impact on plant growth and yield parameters. Temporal densities of thrips, feeding injury from thrips, cotton growth and reproductive profiles, yield, and fiber quality varied with cover crops and irrigation levels. Thrips densities were conspicuously low due to harsh weather conditions, but the densities decreased with an increase in plant age. Terminated rye and wheat cover versus conventional-tilled, no-cover treatments showed marginal effects on thrips colonization and population dynamics. Similarly, full irrigation treatment supported higher thrips densities compared to rainfed and deficit irrigation treatments. Immature thrips densities increased through the successive sampling periods, indicating increased thrips reproduction following the initial colonization. Thrips feeding injury was significantly greater in no-cover plots in the early seedling stage, but the effect was insignificant across all cover crop treatments in subsequent sampling dates. The results of this study demonstrated increased seedling vigor, plant height, and flower densities in terminated cover crop plots across all irrigation regimes compared to that in no-cover plots. However, the cover crop × irrigation interaction significantly impacted the cotton lint yield, with increased lint yield on cover crop treatments. This study clearly demonstrates the value of cover crops in semi-arid agricultural production systems that are characterized by low rainfall, reduced irrigation capacity, and wind erosion of topsoil.

Keywords: cotton; cover crop; thrips; fiber quality; Texas high plains



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1. Introduction

Cotton is a major irrigated crop grown in the Texas High Plains, the most concentrated cotton production region in the world, that contributes to about 25% of the U.S. cotton production and 64% of the Texas cotton production [1]. The declining groundwater level and the restriction of groundwater use for irrigation in the Texas High Plains region have warranted a renewed focus on irrigation management strategies for saving water. Cotton is highly adaptable to drought conditions; alternative approaches such as cover crops help to reduce water in cotton production compared to other crops, the heat tolerance capacity and relatively low water requirements make cotton ideal for the Texas High Plains [2]. Since at least 3000 years ago, cover crops have been used in agriculture. They are thought to reduce soil erosion, preserve soil nutrients, and enhance the physical characteristics

of the soil [3]. In addition, cover crops help to suppress pests, improve soil water, and increase efficiency through nutrient recycling and crop production. Cover crops benefit semi-arid regions by maintaining live vegetative cover between two main crops [4]. Pest suppression due to increased beneficial arthropods is another benefit of cover crops [5]. The benefits of cover crop utilization depend on the species planted [6]. For example, grass species produce high biomass suppressing weed species, lower erosion, and scavenge nutrients from the soil [7]. Rye (*Secale cereale*) is a commonly grown cover crop either as a sole crop or as a cover crop mix. It is hardier than winter wheat (*Triticum aestivum*), another potential cover crop in the region. It handles the soil conditions better than other cover crops because of its tolerance to aluminum toxicity, saline soils, cool temperatures, and its ability to take up excess nitrogen, preventing environmental contamination through leaching or runoff. Rye matures one week earlier than winter wheat and competes with different weeds, including foxtails (*Alopecurus* spp.), kochia (*Bassia scoporia*), pigweeds such as common amaranth (*Amaranthus retroflexus*), palmer amaranth (*Amaranthus palmeri*), and water hemp (*Amaranthus tuberculatus*) and marehail (*Conyza canadensis*), by allelopathic suppression [8]. The amount of biomass produced by cover crops relates to the overall value of the cover in the agroecosystem which helps in reducing soil compaction and soil erosion while enhancing soil organic matter. Cover crops with varying root types are attributed to reduced soil compaction [6].

Five different species of thrips, including western flower thrips (*Frankliniella occidentalis*), flower thrips (*Frankliniella tritica*), soyabean thrips (*Neohydatothrips variabilis*), onion thrips (*Thrips tabaci*), and tobacco thrips (*Frankliniella fusca*), are known to infest cotton seedlings in the United States [9]. The dominant species is the western flower thrips in Texas cotton [10], and onion thrips are the second most prevalent thrips in the Texas High Plains [11]. Thrips are present on various weed and crop species, including those found in cotton production. For the three types of thrips, tobacco thrips, western flower thrips, and flower thrips, respectively, 29, 28, and 49 plant families have been identified as either feeding hosts, reproductive hosts, or plants that thrips are transients on. These include the Asteraceae, Brassicaceae, Fabaceae, Poaceae, Polygonaceae, Solanaceae, and Convolvulaceae families [11].

Feeding from adult and immature thrips causes excessive vegetative branching, delayed maturity, and stand loss [11]. Thrips generally move from drying winter wheat and weed hosts to the cotton field. Although thrips are prevalent in cotton throughout the growing season, the pre-square stage is when the cotton plant is most susceptible to yield loss (up to seven mainstem node leaves). Thrips are advantageous as an alternate prey for many predators in cotton later in the growing season when their feeding no longer reduces lint yield [12,13]. The triple role of thrips as pests, prey, and predators in cotton makes them important insects infesting cotton throughout the growing season. Thrips injury to pre-squaring cotton often causes crop growth and maturity delays, yield reduction, and compromised fiber properties [14].

An inverse relationship exists between rye ground cover and thrips density in cotton [15]. The wheat residue (surface reflectance) has been shown to reduce thrips populations in cotton but not to the level observed when using insecticides [16]. Although the actual mechanism for reducing thrips after using ground covers is not clear, it is hypothesized that the increase in ground cover confounds host-finding behavior for thrips [17]. The difference in predation in conservation tillage cover crop fields compared to that in the conventional field with no cover is due to the presence of a beneficial predator reservoir in conservation tillage cover crop fields. This may also be a plausible contributing factor in the reduced number of thrips in conservation tillage cover crop fields [15]. The relationship between thrips infestation and seed cotton yield is complex; several stresses in growing conditions, such as cold soil temperatures at planting, additional insect infestations, drought, nematode infestations, plant pathogens, nutrient deficiencies, and herbicide damage, impact the effect of thrips injury on seedling cotton [18]. Cotton often compensates for early season thrips damage under favorable conditions [18].

The objective of this study was to quantify the impact of terminated cover crops on cotton germination, seedling growth, and cotton tolerance to thrips infestation across three irrigation regimes. Specifically, this study examined the interactive effect of cover crop, seedling vigor, and thrips infestations on cotton yield and fiber quality.

2. Materials and Methods

2.1. Experimental Site and Treatments

This study was conducted at Texas A&M AgriLife Research farm in Lubbock, Texas (33.7024, −101.8284; elevation 978 m above mean sea level). The area studied had an average annual maximum and minimum temperatures of 30.4 °C and 3.8 °C, respectively. The research site is a semi-arid region having low rainfall (40 cm annual rainfall). This study was conducted using a split-split plot design with irrigation as the main plot, cover crop as the sub-plot, and thrips augmentation as the sub-sub plot. Irrigation was applied at three levels—high, low, and dryland, two cover crops included rye, wheat, and a control (no cover crop), and insect treatment had two levels—control plots sprayed with an insecticide and thrips augmented to ensure densities at or above treatment threshold. The entire test was replicated four times in a randomized complete block design. The high irrigation treatment consisted of 90% ET (evapotranspiration) replenishment with subsurface drip irrigation during the crop growing season; the low irrigation treatment replenished ~30% evapotranspiration, while the dryland treatment was provided with pre-planting irrigation to ensure proper seed germination and no additional irrigation was provided thereafter. Experimental plots were six 1.01 m wide rows × 23 m long, and 1.5 m wide alleys separated each block.

2.2. Cover Crops, Cotton Planting, and Experimental Plots

Cover crops (rye and wheat) were planted with a seed rate of 33.6 kg/ha in mid-February. Rye and wheat seeds (variety not specified) were taken from bulk seeds (mixed seeds of different varieties). Both cover crops were terminated before the boot stage (around mid-May), the stage of plant growth when the seed head emerges from the sheath of the flag leaf before heading and flowering. The stage of cover crops provided sufficient biomass for ground cover while being tolerant to lodging for the best performance. Herbicide Round-Up™ (Bayer Crop Science, Cary, NC, USA) @ 2.24 kg/ha was used to terminate the crop 48 h after cotton planting so that cover crops would begin wilting and release thrips to germinating cotton seedlings. The cotton variety DP1646B2XF (Bayer Crop Science, Cary, NC, USA) was planted at the rate of 13 seeds/row-meter with a John Deere MaxEmerge planter (Deere & Company, Moline, IL, USA). Each cover crop treatment within each irrigation zone was further divided into two 1.8 m × 1.016 m plots assigned as control or thrips augmentation treatment plots. Thus, the entire experiment consisted of 72 plots (three irrigation zones × three cover treatments × two insect treatments × four replications).

2.3. Thrips Augmentation

Two insect treatment sub-sub-plots were achieved via (1) spraying all control plots (total 36 plots) with insecticide acephate @ 5 g/l throughout the study period to ensure that the control plots were thrips-free, and (2) augmenting thrips to ensure thrips densities at or above treatment threshold of 1 thrips per leaf in all thrips augmentation plots (total 36 plots). Alfalfa terminals with heavy thrips infestation were excised from a healthy alfalfa patch maintained at the field insectary on the research farm and were taken to the thrips augmentation plots to release thrips in designated sections of the plot when cotton seedlings were at 1–2 true leaf stage. The terminals were put at the base of young cotton seedlings. When the alfalfa terminal dried, thrips moved to the young cotton seedlings. Thrips release consisted of approximately 650 thrips/1.8 m × 1.016 m section. The average plant stand within the thrips augmentation section was 13 plants/section. Approximately 50 thrips per cotton seedling were released to ensure sufficient damage even after 80% mortality. Control plots were sprayed on the day of thrips release and again four days

after the release of thrips to eliminate thrips from recolonization in control plots from our augmentation in treatment plots. A second thrips release was performed ten days after the first release to ensure sufficient thrips pressure on growing seedlings. The third spray of insecticide was applied 9–10 days after the second insecticide application in all control plots.

2.4. Thrips Sampling

Pre-treatment thrips sampling was performed in 36 plots before each cover crop treatment was divided into two 1.8 m × 1.016 m sub-plot sections for insect augmentation treatment. When cotton germination was near 100% and seedlings were at cotyledon to 1 true-leaf stage, five cotton seedlings from each plot were randomly selected, quickly pulled from the ground, and collected in a glass jar containing 250 mL of 70% ethyl alcohol to secure thrips in alcohol. The glass jars were taken into the laboratory, where the thrips were separated from plant substrate using the thrips washing technique and the densities were counted (see below). Post-treatment thrips samplings were performed approximately two weeks, three weeks, and five weeks after planting from all 72 plots (a total of three sample dates).

2.5. Thrips Washing and Density Estimation

Collected seedlings (plant substrate and thrips) were rinsed through a No. 30 sieve (to separate plant substrate) on top of a No. 150 sieve (to separate thrips). The jar and the lid over the filter needed to be rinsed properly to prevent the loss of the thrips. Each plant/leaf was carefully rinsed thoroughly to remove any thrips from the plant's substrate. The front and back of the No. 150 sieve were rinsed with a concentrated saltwater solution into a plastic dish. The entire contents of the plastic dish were poured into the separatory funnel. After passing the solution into the separatory funnel, the plastic dish and the funnel were rinsed to remove any thrips that may have been left behind. The water was allowed to settle (ideally, the sand and dirt should settle at the bottom and the thrips towards the top). The content with thrips was poured into its original jar, rinsing everything thoroughly to prevent loss of thrips numbers. The coffee filter was lined with a pen marking different sections so that it would be easy to count thrips under the microscope. The vacuum was used to remove additional moisture from the coffee filter, and once dried, the filter was placed under the microscope to examine and count the number of thrips present in the sample. Adults and immatures were counted separately [19].

2.6. Thrips Damage Rating

Thrips damage rating was conducted at the 4th true leaf stage and 8–10th true leaf stage to assess the relative damage on cotton seedlings by thrips feeding. The damage ratings used a 0–5 scale where '0' represented lack of thrips injury and '5' represented the most severe injury, resulting in the death of the plant's terminal growing point, severely stunted plants, and curling of most true leaves [20].

2.7. Flower Monitoring and Plant Height Measurement

Flower monitoring was conducted daily in all 72 experimental plots from flowering initiation to crop termination. Plant height was also taken from all 72 plots, where five consecutive plants were measured around the center of the plot. The ruler was used to measure the height of the cotton plant from the cotyledon node to the terminal (apical point) of the cotton plant. Plant height was taken at weekly intervals.

2.8. Cotton Termination and Harvesting

Harvest aids Boll'd® 6SL (Ethephon [(2-chloroethyl) phosphonic acid] @ 2.3 L/ha (boll opener) and ET®X (Pyraflufen ethyl) 110 mL/ha (desiccant) were applied when cotton was sufficiently matured for crop termination (60% cracked boll) to accelerate opening of matured unopened bolls and begin the defoliation process. Gramoxone® SL 3.0 @ 1.7 kg/ha

sprayed two weeks after the application of desiccant to ensure complete crop defoliation. Test plots were hand-harvested and a subsample of 500 g of seed cotton was ginned for lint yield estimation and fiber quality analysis.

2.9. Data Analysis

Data were analyzed using R software version 4.1.3. Inferential statistics such as analysis of variance (ANOVA) were estimated for treatments and their interactions. Assumptions of ANOVA were met using Global Validation for Linear Model Assumption (GVLMA) where global stat, skewness, kurtosis, and link function were satisfied and acceptable. In addition, means were separated using the least significant difference (LSD) test at a ≤ 0.1 . Pearson's correlation and regression analyses were conducted to establish relationships between number of white flowers per hectare at three crop phenological stages and average fiber yield (kg/ha).

3. Results

3.1. Thrips Establishment and Abundance

Thrips densities were uncharacteristically low in the Texas High Plains region during the study years due to unusually harsh weather conditions including incessant windstorms. Nevertheless, thrips were colonized in the test plots and limited information was collected (Table 1). There was a decreasing trend of immature thrips densities from 2 June 2022 (two true-leaf stage) to 7 June 2022 (three true-leaf stage), but there was no significant difference in the average density of thrips nymphs among three irrigation levels (df = 2, 4; F = 0.35, $p = 0.71$; df = 2, 4; F = 0.07, $p = 0.92$) or three cover crop treatments (df = 2, 4; F = 1.30, $p = 0.29$; df = 2, 4; F = 2.23, $p = 0.13$) in both sampling dates. However, average number of thrips adults increased from 2 June to 7 June; high irrigation treatment attracted significantly greater number of adult thrips when seedlings were at 3–4 leaf stage (df = 2, 4; F = 4.75, $p = 0.05$) but the effect of cover crop treatment was also insignificant for adult thrips activity (df = 2, 4; F = 0.37, $p = 0.69$) in the year 2022. In 2023, immature thrips densities marginally increased in the second sampling date, whereas thrips adult densities decreased. No significant differences were observed in thrips densities due to cover crop or irrigation treatments.

Table 1. The average total nymphs and adults ($\pm$ SEM) per five plants as influenced by irrigation and cover crop at different true leaf stages in the years 2022 and 2023.

Treatments	2022				2023			
	Nymphs (1–2 Leaf)	Number of Thrips		Adults (3–4 Leaf)	Nymphs (1–2 Leaf)	Number of Thrips		Adults (3–4 Leaf)
		Adults (1–2 Leaf)	Nymphs (3–4 Leaf)			Adults (1–2 Leaf)	Nymphs (3–4 Leaf)	
Irrigation								
High	4.67 a (0.8)	2.00 a (0.2)	1.67 a (0.4)	4.91 a (0.6)	1.16 a (0.3)	1.08 a (0.3)	1.58 a (0.3)	0.66 a (0.2)
Low	3.67 a (0.5)	1.58 a (0.3)	1.50 a (0.2)	2.83 b (0.3)	0.41 b (0.2)	1.66 a (0.3)	1.91 a (0.5)	0.58 a (0.2)
Dryland	3.50 a (0.7)	2.58 a (0.6)	1.41 a (0.2)	3.08 b (0.6)	0.33 b (0.1)	0.91 a (0.2)	1.25 a (0.3)	0.16 a (0.1)
Cover Crop								
Rye	3.33 a (0.5)	2.00 a (0.3)	1.41 a (0.2)	3.58 a (0.7)	0.75 ab (0.2)	0.91 a (0.3)	1.00 b (0.2)	0.16 a (0.1)
Wheat	3.83 a (0.6)	2.41 a (0.5)	2.00 a (0.3)	3.91 a (0.3)	1.00 a (0.3)	1.41 a (0.2)	2.25 a (0.5)	0.58 a (0.2)
Fallow	4.67 a (0.9)	1.75 a (0.4)	1.16 a (0.2)	3.33 a (0.7)	0.16 b (0.1)	1.33 a (0.2)	1.50 ab (0.3)	0.66 a (0.3)

The values in the parentheses indicate standard errors. The means that are followed by different letters within the column for the irrigation and cover crop main treatment rows are significantly different ($p < 0.01$).

Averaged over two years, average immature thrips densities were 1.6, 1.8, and 2.2 thrips per sample in dryland, low irrigation, and high irrigation treatments, respectively, whereas adult thrips densities were 1.6, 1.5, and 2.1 thrips per sample in respective irrigation treatments (Table 2). Although statistically not significant, high irrigation plots attracted more adult thrips and consequently greater immature thrips densities compared to that in low irrigation and dryland treatment plots. In the high irrigation zone, fallow and wheat plots numerically exceeded rye cover plots in thrips nymphs ($df = 2, 6$; $F = 1.42$, $p = 0.31$) whereas in low irrigation ($df = 2, 6$; $F = 0.06$, $p = 0.93$) and dryland zones ($df = 2, 6$; $F = 1.0$, $p = 0.42$), average density of thrips nymphs was marginally higher in wheat cover compared to rye and fallow plots with no significant difference among rye, wheat, and fallow plots. Cover crops, although not statistically significant, showed marginal affinity of thrips toward wheat cover (2.2 immature and 2.1 adult thrips per sample) compared to fallow (1.6 immature and 1.6 adult thrips per sample) and rye cover (1.8 immature and 1.5 adult thrips per sample) (Table 2). Nevertheless, there was a significant interaction in irrigation and cover crop treatments that impacted thrips colonization performance ($df = 4, 4$; $F = 2.50$, $p = 0.07$). For example, dryland wheat cover crops attracted a greater number of adult thrips compared to rye cover and fallow plots ($df = 2, 6$; $F = 12.11$, $p = 0.008$) (Table 2).

Table 2. Average density ($\pm$ SEM) of thrips as influenced by cover crops within each of the three irrigation treatments, 2022–2023, Lubbock, TX, USA.

Irrigation	Cover Crops								
	2022			2023			Average		
	Fallow	Rye	Wheat	Fallow	Rye	Wheat	Fallow	Rye	Wheat
Nymphs									
Dryland	2.3 a (0.7)	2.7 a (0.5)	2.5 a (0.5)	0.6 a (0.2)	0.7 a (0.1)	1.0 a (0.6)	1.5 a (0.3)	1.7 a (0.2)	1.7 a (0.2)
Low	2.3 a (0.5)	2.1 a (0.4)	3.0 a (0.4)	0.7 a (0.4)	0.7 a (0.4)	2.0 a (0.8)	1.5 b (0.4)	1.4 b (0.4)	2.5 a (0.6)
High	4.0 a (0.8)	2.2 a (0.4)	3.2 a (0.6)	1.1 a (0.2)	1.1 a (0.1)	1.8 a (0.4)	2.5 a (0.5)	1.6 ab (0.2)	2.5 a (0.4)
Adults									
Dryland	2.0 b (0.7)	2.3 b (0.3)	4.1 a (0.5)	0.5 a (0.2)	0.3 a (0.2)	0.7 a (0.3)	1.2 b (0.3)	1.3 b (0.2)	2.4 a (0.1)
Low	1.7 a (0.5)	2.1 a (0.3)	2.7 a (0.2)	1.5 a (0.2)	0.7 a (0.4)	1.1 a (0.3)	1.6 ab (0.2)	1.4 b (0.2)	1.9 a (0.2)
High	3.8 a (0.7)	3.8 a (0.5)	2.6 a (0.3)	1.0 a (0.5)	0.5 a (0.3)	1.1 a (0.5)	2.4 a (0.4)	2.1 ab (0.2)	1.8 b (0.3)

Values in the parentheses indicate standard errors. Means followed by different letters between cover crop treatments within each irrigation treatment and year are significantly different ($p < 0.01$).

3.2. Thrips Injury

As stated earlier, thrips infestation was quite low in both study years to exert significant injury to the growing seedlings. Nevertheless, thrips injury rating ranged from zero to 3.2 (Table 3). Thrips injury infliction was negligible in 2022 while the injury infliction to seedlings was much more pronounced in 2023; the low-level injury did not allow statistical separation across treatments (Table 3). Although few injury rating values were statistically significant (Table 3), plant damages with injury ratings of 3 or less are quickly overcome by growing seedlings and the carryover effect of such injury is not biologically relevant.

Table 3. Average ($\pm$ SEM) thrips injury ranking of seedling cotton as influenced by cover crops within each irrigation treatment, 2022–2023.

Irrigation	Cover Crops								
	2022			2023			Average		
	Fallow	Rye	Wheat	Fallow	Rye	Wheat	Fallow	Rye	Wheat
Injury Level (1–2 true leaf stage)									
Dryland	1.4 a (0.08)	1.1 b (0.05)	1.1 b (0.1)	1.8 ab (0.3)	1.3 b (0.2)	2.25 a (0.3)	1.6 a (0.2)	1.2 b (0.1)	1.6 a (0.2)
Low	1.2 a (0.2)	0.9 a (0.2)	1.0 a (0.1)	1.7 a (0.3)	1.9 a (0.5)	1.8 a (0.4)	1.4 a (0.1)	1.4 a (0.2)	1.6 a (0.3)
High	1.1 a (0.2)	1.0 a (0.2)	1.5 a (0.1)	2.0 a (0.3)	1.8 a (0.5)	2.4 a (0.4)	1.6 a (0.2)	1.3 a (0.3)	1.7 a (0.1)
Injury Level (5–6 true leaf stage)									
Dryland	0.05 a (0.05)	0.0 a (0.0)	0.10 a (0.05)	3.1 a (0.1)	2.5 a (0.3)	3.2 a (0.3)	1.6 a (0.09)	1.2 a (0.1)	1.6 a (0.2)
Low	0.0 a (0.0)	0.0 a (0.0)	0.10 a (0.1)	2.6 a (0.1)	1.8 b (0.2)	2.7 a (0.4)	1.3 a (0.09)	0.9 a (0.1)	1.4 a (0.2)
High	0.05 a (0.05)	0.05 a (0.05)	0.10 a (0.05)	3.2 a (0.3)	2.8 a (0.4)	3.0 a (0.5)	1.6 a (0.1)	1.4 a (0.2)	1.5 a (0.2)

Values in the parentheses indicate standard errors. Means followed by different letters between cover crops within irrigation treatment and year are significantly different ($p < 0.01$, $df = 2$, $f = 6.48$).

3.3. Plant Height

Irrigation had a significant effect on plant height as the season progressed in both study years. In 2022, as expected, cotton height was significantly influenced by sample date ($df = 6, 24$; $F = 323.36$, $p < 0.0001$). High and low irrigation plots were not significantly different until July 29 (during mid-flowering) (Figure 1), but after that, on two sampling dates, cotton height was significantly different in high and low irrigation plots. Cotton height in dryland differed significantly from both high and low irrigation plots in all sampling dates ($df = 2, 24$; $F = 122.40$, $p < 0.0001$). Similarly, cotton height was significantly influenced by cover crops ($df = 2, 24$; $F = 13.09$, $p < 0.0001$). Cotton plants on cover crop plots (rye and wheat cover plots) were significantly taller than in fallow (no cover plots) until 8 July 2022 (first flowering). From 15 July (flowering) to 12 August 2022 (boll initiation), there was no significant difference in height between the rye and fallow plots. After 29 July 2022 (mid-flowering), the average height of cotton plants in rye and fallow plots was nearly the same. On 12 August (boll initiation), the fallow plot overtook the rye plot even though the difference was marginally significant. Cotton heights in wheat cover were significantly greater than in fallow plots throughout the sampling period. Cotton plants were marginally taller in sprayed plots compared to those in thrips-augmented plots ($df = 1, 24$; $F = 12.22$, $p < 0.0005$). The interaction of sampling date and irrigation ($df = 12, 24$; $F = 4.60$, $p < 0.0001$), irrigation and insect ($df = 2, 24$; $F = 13.23$, $p < 0.0001$), irrigation and cover crop ($df = 4, 24$; $F = 3.04$, $p = 0.0173$), insect and cover crop ($df = 2, 24$; $F = 5.80$, $p = 0.0033$), and irrigation, insect treatment, and cover crop ($df = 4, 24$; $F = 6.54$, $p < 0.0001$) all significantly influenced plant height.

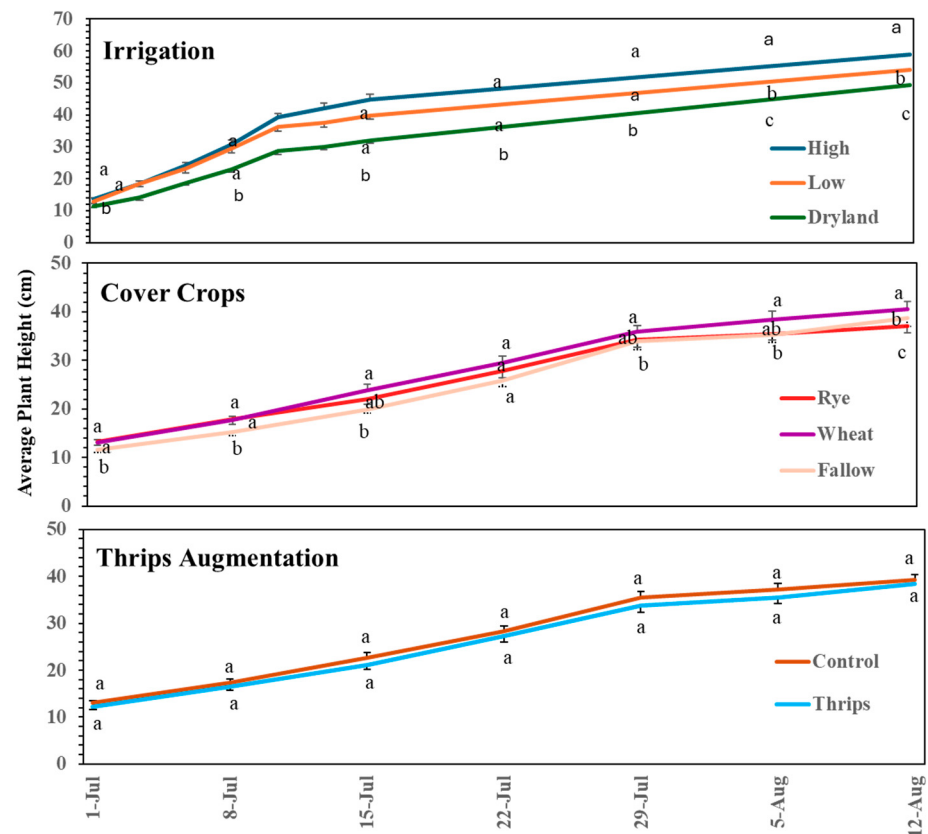


Figure 1. Temporal change in plant height influenced by irrigation level, cover crop type, and thrips treatment Lubbock, TX, USA, 2022. Values with different lowercase letters within each sampling date are significantly different ($p < 0.1$).

In 2023, the effect of sampling date ($df = 8, 32$; $F = 142.46$, $p < 0.0001$), irrigation ($df = 2, 32$; $F = 23.50$, $p < 0.0001$), and cover crop ($df = 2, 32$; $F = 4.23$, $p = 0.0151$) to plant height was similar to that for 2022 (Figure 2), but unlike 2022, thrips infestation did not significantly influence plant height. No significant difference was observed between low and high irrigation plots throughout the growing season, but high irrigation plots had taller plants compared to low water and dryland plots throughout the growing season with significant differences between high irrigation and dryland plots in some growth stages such as 10–12 true leaf stages and boll initiation. After boll initiation, no significant difference was observed among high, low, and dryland plots. There was no significant difference between rye and wheat cover plots throughout the growing season, but significant differences were observed between wheat cover plots and fallow plots until squaring and after that, no significant difference among rye, wheat, and fallow cover plots was observed. Similarly, thrips treatment did not impact plant height in any growth stages in 2023. Unlike 2022, the interaction between sampling date and irrigation as well as irrigation and insect did not influence plant height. The interaction between irrigation and cover crop ($df = 4, 32$; $F = 13.85$, $p < 0.0001$), insect and cover crop ($df = 2, 32$; $F = 12.92$, $p < 0.0001$), and irrigation, insect, and cover crop ($df = 4, 32$; $F = 4.90$, $p = 0.0007$) significantly influenced plant height as in 2022.

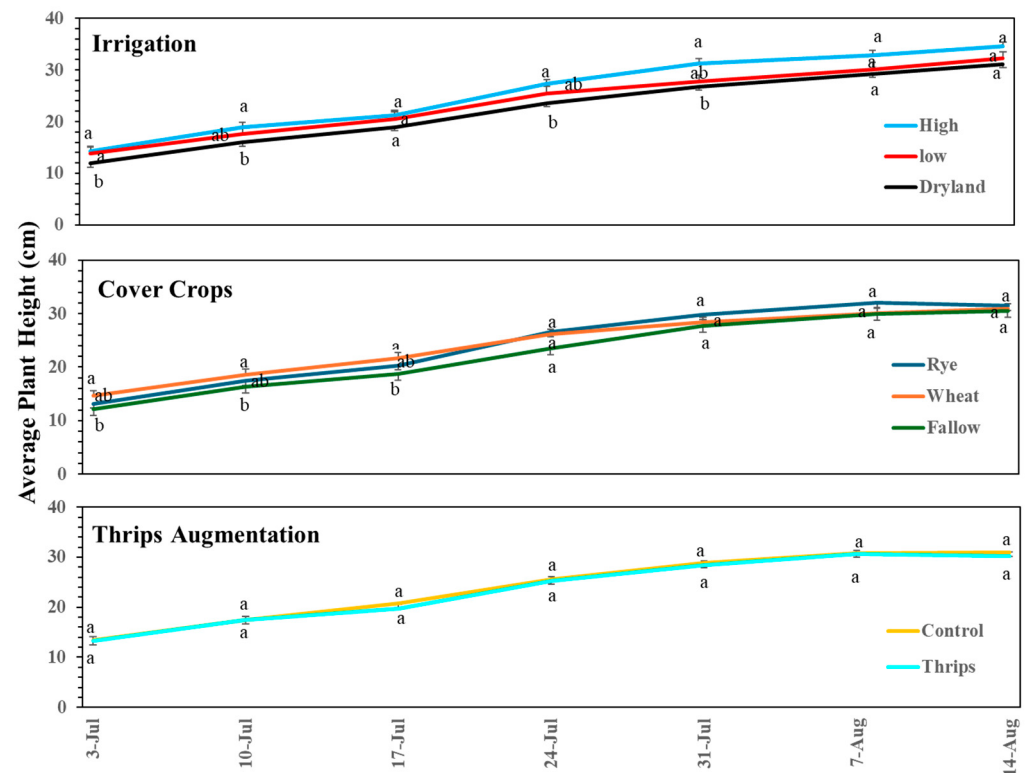


Figure 2. Temporal change in plant height influenced by irrigation level, cover crop type, and thrips treatment Lubbock, TX, USA, 2023. Values with different lowercase letters within each sampling date are significantly different ($p < 0.1$).

3.4. Flowering Profile and Flower Density

Cotton flowering phenology was highly influenced by irrigation, cover crop types, and their interactions in both years. In 2022, the density of total daily white flowers varied significantly with sample date ($df = 38, 152$; $F = 64.05$, $p < 0.001$). Also, irrigation had a significant influence on the number of daily total white flowers across all sampling dates ($df = 2, 152$; $F = 224.0$, $p < 0.001$; Figure 3). High and low irrigation plots had significantly greater flower densities than dryland plots until mid-August when plants achieved 70% of the flowers. Nevertheless, both high and low-water plots had a greater number of flowers than dryland plots throughout the flowering period until plant cut-out (Figure 3). The high-water plots had significantly greater flower densities all throughout the growing season compared to those in dryland plots. Similarly, the cover crop significantly influenced the number of daily total white flowers ($df = 2, 152$; $F = 13.0$, $p < 0.001$). Cover crop plots had significantly greater cotton flower densities than cotton planted in fallow plots until mid-August and the difference dissipated as the season progressed and plants entered the fruit maturation phase. Flower densities were higher in sprayed control plots compared to those in thrips augmented plots ($df = 1, 152$; $F = 15.48$, $p < 0.001$). (Figure 3). The interaction of sampling date and irrigation ($df = 76, 152$; $F = 2.81$, $p < 0.001$), sampling date and cover crop ($df = 76, 152$; $F = 2.13$, $p < 0.001$), irrigation and cover crop ($df = 4, 142$; $F = 9.06$, $p < 0.001$), irrigation and insect ($df = 2, 152$; $F = 5.86$, $p = 0.002$), cover crop and insect ($df = 2, 152$; $F = 6.48$, $p = 0.0015$), sampling date, irrigation and cover crop ($df = 152, 152$, $F = 1.96$, $p < 0.001$), and irrigation, cover crop, and insect ($df = 4, 152$; $F = 9.28$, $p < 0.001$) all influenced the number of daily total white flowers.

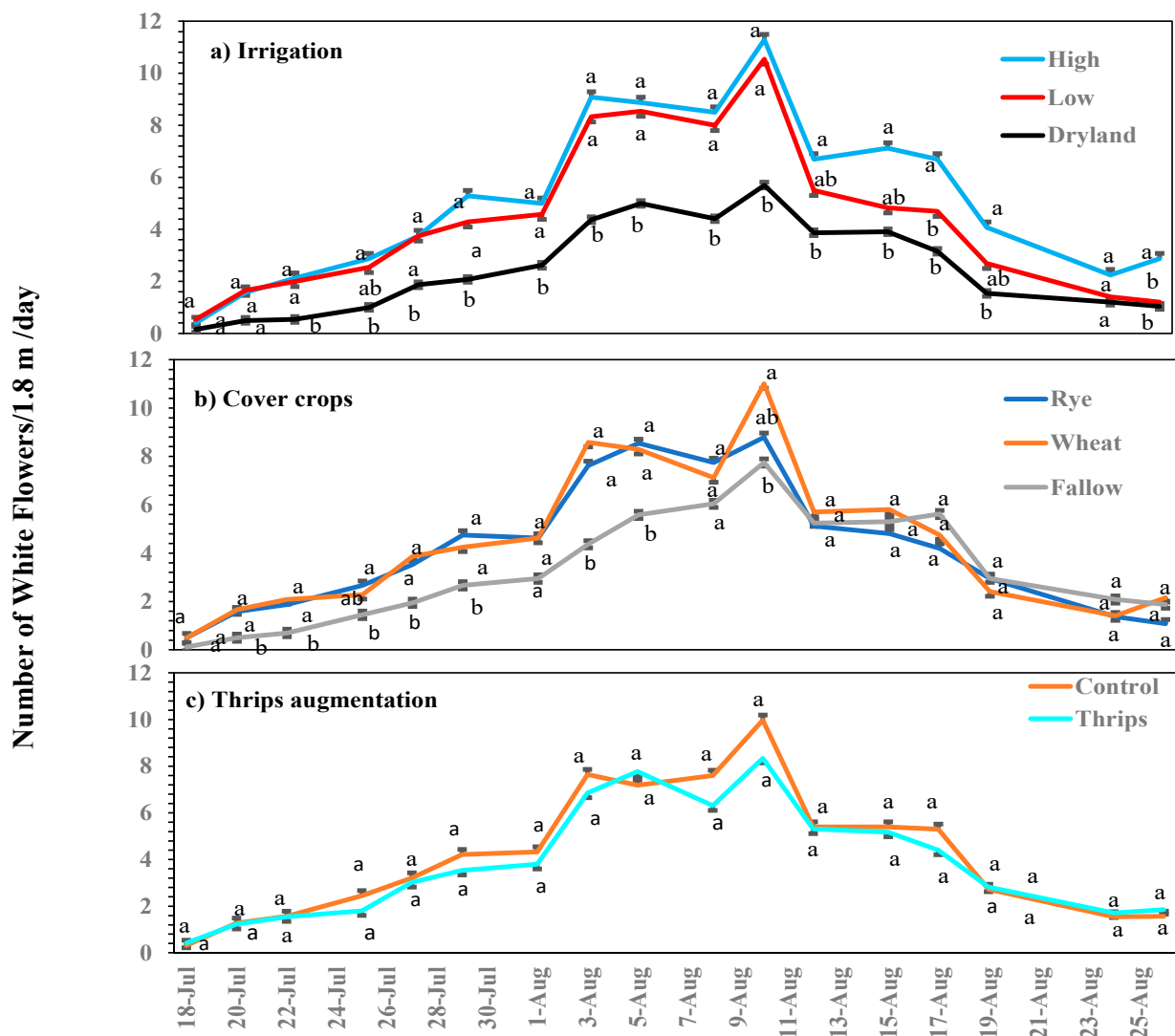


Figure 3. White flowers in cotton were influenced by irrigation level, cover crop type, and thrips treatment in the year 2022. Values with different lowercase letters within each sampling date are significantly different ($p < 0.1$).

Averaged over the entire growing season, high irrigation plots had significantly greater densities of white flowers ($df = 2, 4$; $F = 25.35$, $p = 0.001$), followed by low irrigation and the lowest densities of flowers were observed in dryland plots (Figure 4). Overall, cover crop plots had greater densities of flowers than no-cover plots; wheat cover plots had the highest seasonal average flower densities, followed by rye cover and the lowest flower abundance was observed in no-cover plots with no significant difference among them ($df = 2, 4$; $F = 2.28$, $p = 0.13$). Thrips augmented plots had insignificantly lower flower abundance than sprayed control plots ($df = 1, 4$; $F = 2.54$, $p = 0.12$). The interaction of irrigation and cover crop did not significantly influence the number of seasonal total white flowers ($df = 4, 4$; $F = 1.59$, $p = 0.21$).

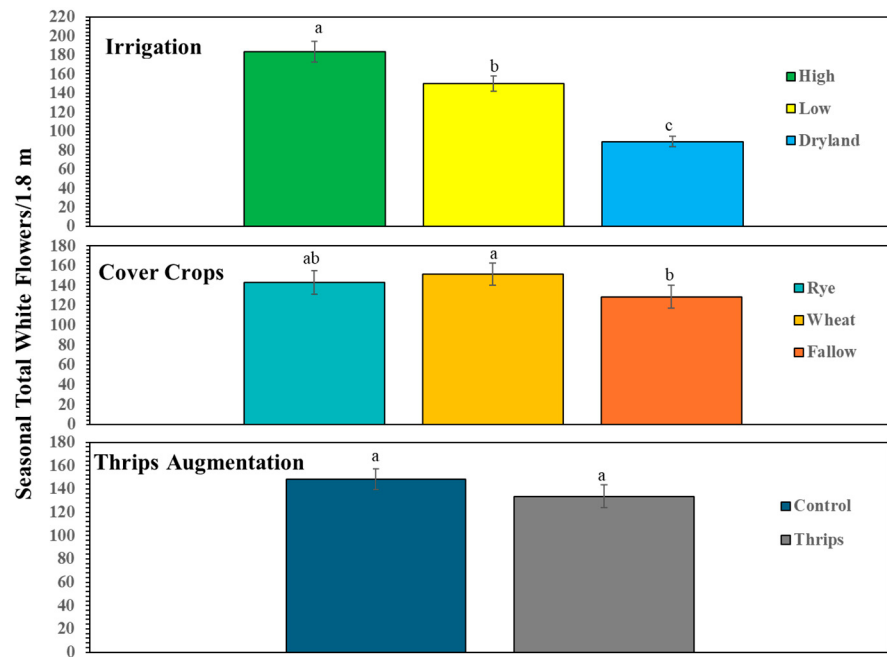


Figure 4. Average seasonal white flower density (total flowers per 1.8 m cotton row) influenced by irrigation level, cover crop type, and thrips augmentation. Bars above the mean values are standard errors. Bars with different letters indicate significant differences between treatments. Lubbock, TX, USA, 2022.

The 2023 flowering phenology and flower profiles were generally similar to that for 2022 (Figure 5). Sampling dates ($df = 38, 152$; $F = 42.87, p < 0.001$), irrigation ($df = 2, 152$; $F = 4.2, p = 0.015$), cover crop ($df = 2, 152$; $F = 15.95, p < 0.001$), and insect ($df = 1, 152$; $F = 4.34, p = 0.037$) significantly influenced the number of daily total white flowers. The high and low-water plots had higher flower densities than dryland plots for the first half of the flowering season and then the difference dissipated as the season progressed. Specifically, the high-water plots had significantly greater densities of white flowers than low-water or dryland plots. Cover crop plots also resulted in greater flower densities during the first half of the flowering period with significant differences between wheat and fallow plots in some sampling dates and the effect of cover crops dissipated as the season progressed. The 2023 season was a bit more unusual than in 2022 as the high-water plots produced greater flower densities in the first half of the flowering period with a significant difference between high-water plots and dryland in some sampling dates, but the plants produced significantly lower flower densities as the season progressed. The flower densities were significantly influenced by thrips augmentation in 2023 ($df = 1, 152$; $F = 4.3, p = 0.037$). The interactions of sampling date and irrigation ($df = 76, 152$; $F = 3.07, p < 0.001$), sampling date and cover crop ($df = 76, 152$; $F = 5.7, p < 0.001$), irrigation and insect ($df = 2, 152$; $F = 13.68, p < 0.001$), cover crop and insect ($df = 2, 152$; $F = 7.92, p = 0.0003$), sampling date, irrigation, and cover crop ($df = 152, 152$; $F = 1.78, p < 0.001$), and irrigation, cover crop, and insect ($df = 4, 152$; $F = 4.45, p = 0.0013$) all significantly influenced the number of daily total white flowers.

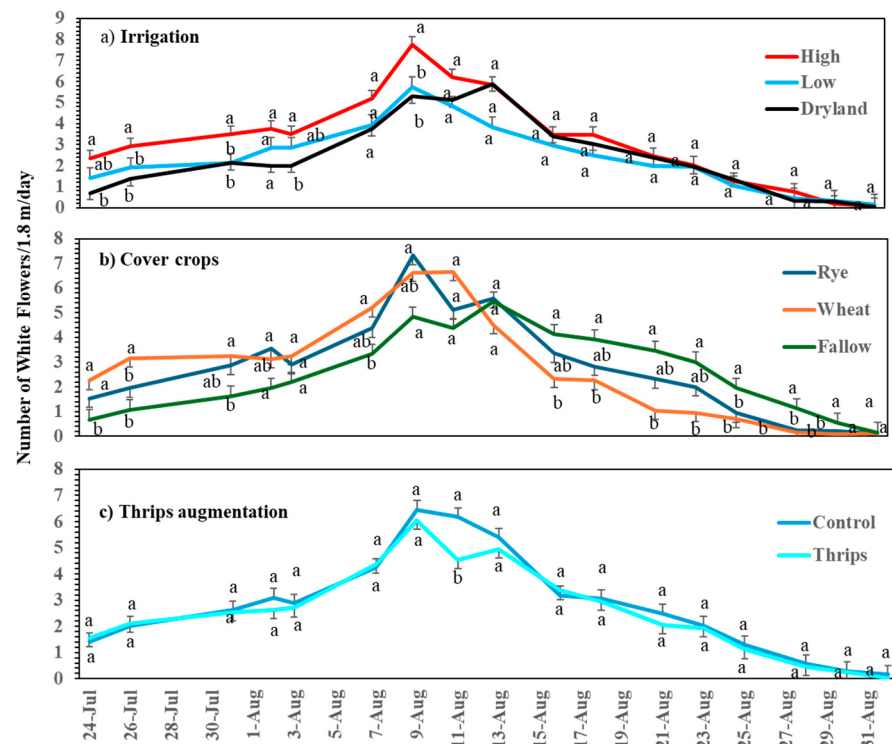


Figure 5. Average daily total flowers per 1.8 m cotton row influenced by irrigation level, cover crop type, and thrips augmentation. Bars above the mean values are standard errors. Values with different letters within each sampling date indicate significant differences between treatments. Lubbock, TX, USA, 2023.

Averaged over the entire growing season, high irrigation plots had significantly greater flower abundance than low irrigation or dryland plots ($df = 2, 4$; $F = 6.11$, $p = 0.035$) (Figure 6). Both cover crop treatments resulted in marginally greater flower abundance but no statistical significance ($df = 2, 4$; $F = 1.72$, $p = 0.20$) while thrips augmentation had no noticeable impact on flower densities ($df = 1, 4$; $F = 0.75$, $p = 0.39$). As in the year 2022, there was no significant difference due to the interaction of irrigation and cover crop on seasonal total flowers ($df = 4, 4$; $F = 1.45$, $p = 0.25$) but unlike 2022, the interaction of irrigation, cover crop, and insect had a significant influence on seasonal total flowers ($df = 4, 4$; $F = 2.27$, $p = 0.08$) (Table 4).

Table 4. Total daily white flowers ($\pm$ SEM) as influenced by cover crops within each irrigation level, 2022–2023.

Irrigation	Cover Crops								
	2022			2023			Average		
	Fallow	Rye	Wheat	Fallow	Rye	Wheat	Fallow	Rye	Wheat
Dryland	70.9 b (10.8)	93.5 ab (5.3)	102.8 a (8.3)	73.6 b (6.1)	123.4 a (14.4)	123.0 a (6.2)	72.2 b (6.1)	108.4 a (6.9)	112.9 a (4.8)
Low	152.7 a (9.0)	157.1 a (18.6)	140.4 a (13.1)	99.2 b (19.0)	130.4 a (9.6)	124.2 ab (11.7)	126.0 a (12.3)	143.8 a (9.3)	132.3 a (10.6)
High	161.7 a (20.0)	178.5 a (20.7)	210.4 a (12.5)	165.8 a (23.7)	140.1 a (22.3)	164.4 a (9.7)	163.7 a (17.9)	159.3 a (13.2)	187.4 a (5.8)

Values in the parenthesis indicate standard errors. Means followed by different letters along each row for each cover crop within the year and average are significantly different ($p < 0.1$).

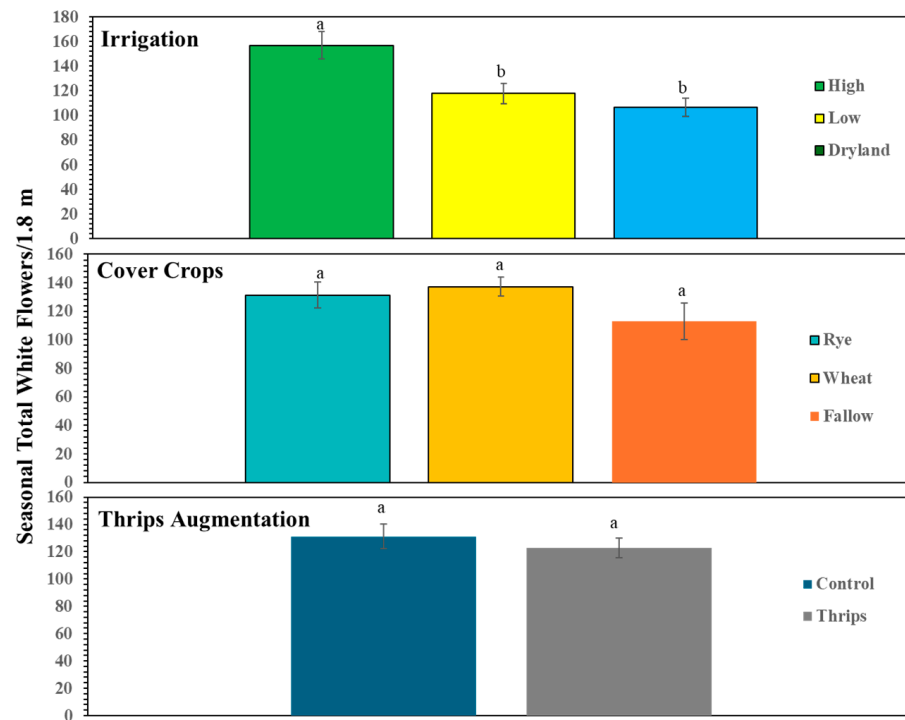


Figure 6. Average seasonal white flower density (total flowers per 1.8 m cotton row) influenced by irrigation level, cover crop type, and thrips augmentation. Bars with different letters indicate significant differences between treatments. Lubbock, TX, USA, 2023. Values with different lowercase letters within each main treatment are significantly different ($p < 0.1$).

3.5. Lint Yield

As expected, irrigation had a significant impact on lint yield in both study years. In 2022, irrigation level had a characteristic staircase effect with significantly highest lint yield in high water treatment (988.5 kg/ha), followed by low water (621.5 kg/ha), and the least amount of lint yield in dryland (274.6 kg/ha) plots ($df = 2, 4$; $F = 21.07$, $p = 0.0019$) (Figure 7). In 2023, both irrigation treatments had significantly greater lint yield (high water: 626.0 kg/ha and low water: 513.0 kg/ha) than dryland (250.5 kg/ha) plots ($df = 2, 4$; $F = 25.36$, $p = 0.0011$), but the yield between the two water levels was not statistically different (Figure 8). No significant effect of cover crops or thrips augmentation on lint yield was observed in either study years ($df = 2, 1, 4$; $F = 0.96, 2.51$, $p > 0.1$) (Figures 7 and 8). The interaction of irrigation and cover crop had no significant differences in the lint yield in 2022 ($df = 4, 4$; $F = 1.31$, $p = 0.30$) but a significant difference was observed in the year 2023 ($df = 4, 4$; $F = 5.02$, $p = 0.0067$). Averaged over two years, dryland, low-water, and high-water treatments produced 262.6, 567.2, and 807.3 kg/ha, respectively, with significantly increased yield with increased level of irrigation water ($df = 2, 4$; $F = 28.80$, $p = 0.0008$) (Table 5). Cover crop and thrips augmentation treatments did not significantly influence the lint yield when combined over two years (cover crop: $df = 2, 4$; $F = 0.85$, $p = 0.44$; thrips augmentation: $df = 1, 4$; $F = 0.48$, $p = 0.49$).

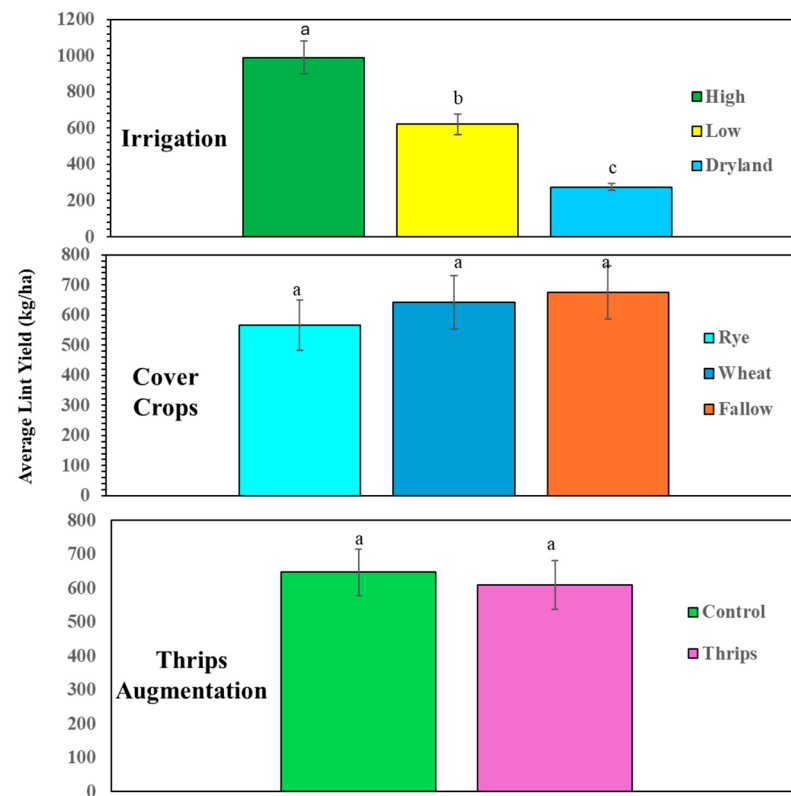


Figure 7. Average ($\pm$ SEM) lint yield influenced by irrigation level, cover crop, and thrips augmentation, Lubbock, TX, USA, 2022. Values with different lowercase letters within each main treatment are significantly different ($p < 0.1$).

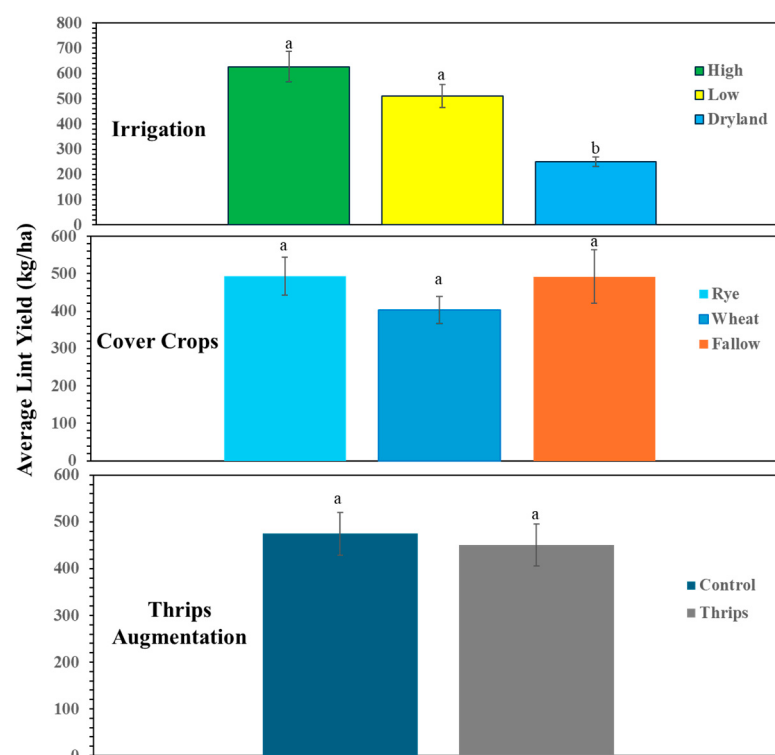


Figure 8. Average ($\pm$ SEM) lint yield influenced by irrigation level, cover crop, and thrips augmentation, Lubbock, TX, USA, 2023. Values with different lowercase letters within each main treatment are significantly different ($p < 0.1$).

Table 5. Average ($\pm$ SEM) lint yield (kg/ha) as influenced by cover crops within each irrigation level, 2022–2023.

Irrigation	Cover Crops								
	2022			2023			Average		
	Fallow	Rye	Wheat	Fallow	Rye	Wheat	Fallow	Rye	Wheat
Dryland	249.5 a (22.3)	255.4 a (34.5)	318.9 a (39.8)	205.4 a (28.5)	294.2 a (39.1)	252.0 a (28.5)	227.5 a (12.9)	274.8 a (21.0)	285.4 a (25.4)
Low	752.3 a (60.8)	605.8 a (131.5)	506.4 a (76.8)	464.6 b (84.3)	652.8 a (69.6)	421.5 b (65.4)	608.4 a (59.4)	629.3 a (73.8)	464.0 a (66.2)
High	1025.6 a (169.4)	838.0 a (156.9)	1101.8 a (148.6)	806 a (130.2)	538.1 b (96.0)	534.0 b (50.1)	915.9 a (81.3)	688.0 b (74.4)	817.9 ab (74.7)

Values in the parenthesis indicate standard errors. Means followed by different letters for each cover crop along each row within a year or average are significantly different ($p < 0.1$).

3.6. Fiber Properties

Fiber quality parameters affect the lint value and ultimately the price the lint fetches at the sale point. Six cotton fiber parameters are generally used in determining the price of the lint. Irrigation water level, cover crops, and insect augmentation impacted various fiber quality parameters, but there was much variation in the impact of these independent variables.

3.6.1. Micronaire

In 2022, micronaire values for the lint from fallow, rye, and wheat plots were identical (4.2 or a premium fiber) for dryland (Table 6). The micronaire value between 3.7 and 4.2 is considered a premium cotton that fetches additional value above the base range (3.5 to 3.6 or 4.3 to 4.9) whereas the values below 3.4 or above 5.0 will suffer discounted price [2]. No-cover (fallow) plots had micronaires in the premium range regardless of the irrigation level, whereas fibers in cover crops had micronaires generally in a base range, except for fallow (Table 6). In 2023, micronaire values were within the base range in all treatment combinations (Table 7).

Table 6. Average fiber quality parameters ($\pm$ SEM) influenced by cover crops within each irrigation level in the year 2022.

Irrigation	Cover Crops		
	Fallow	Rye	Wheat
Fiber Quality Parameter			
Micronaire (MIC)			
Dryland	4.2 (0.09)	4.2 (0.09)	4.2 (0.09)
Low	4.1 (0.1)	4.3 (0.1)	4.5 (0.08)
High	3.9 (0.2)	4.3 (0.1)	4.3 (0.09)
Short fiber index (SFI)			
Dryland	10.5 (0.3)	10.5 (0.3)	10.5 (0.3)
Low	9.9 (0.4)	10.2 (0.4)	10.8 (0.3)
High	10.0 (0.5)	9.9 (0.5)	9.4 (0.5)
Upper half mean length (UHML)			
Dryland	1.12 (0.005)	1.12 (0.005)	1.12 (0.005)
Low	1.16 (0.01)	1.13 (0.009)	1.13 (0.01)
High	1.17 (0.01)	1.16 (0.01)	1.17 (0.01)
Uniformity index (UI)			
Dryland	80 (0.19)	80 (0.19)	80 (0.19)
Low	81 (0.3)	81 (0.3)	80 (0.3)
High	81 (0.3)	81 (0.4)	81 (0.4)

Table 6. Cont.

Irrigation		Cover Crops	
Fiber Quality Parameter	Fallow	Rye	Wheat
Strength (STR)			
Dryland	27 (0.22)	27 (0.22)	27 (0.22)
Low	27 (0.4)	27 (0.3)	27 (0.4)
High	27 (0.2)	27 (0.2)	27 (0.2)
Elongation (ELO)			
Dryland	7.4 (0.06)	7.4 (0.06)	7.4 (0.06)
Low	7.6 (0.06)	7.6 (0.06)	7.7 (0.04)
High	7.9 (0.06)	7.9 (0.03)	8.0 (0.1)

Values in parentheses indicate standard errors. Micronaire: 3.5–3.6 and 4.3–4.9—base, 3.7 to 4.2—premium, and <3.5 and >4.9—discount values; strength (g/tex): 26.0 to 28.9—base, >29.0—premium, and <26.0—discount values; fiber length uniformity: 80.0 to 81.9—base, >81.9—premium, and <80.0—discount values; elongation (%): <5.0—very low, 5.0–5.8—low, 5.9–6.7—average, 6.8–7.6—high, and >7.6—very high.

Table 7. Average fiber quality parameters ($\pm$ SEM) influenced by cover crops within each irrigation level in the year 2023.

Irrigation		Cover Crops		
Fiber Quality Parameter	Fallow	Rye	Wheat	
Micronaire (MIC)				
Dryland	4.5 (0.04)	4.4 (0.09)	4.4 (0.02)	
Low	4.6 (0.04)	4.6 (0.07)	4.8 (0.05)	
High	4.5 (0.04)	4.7 (0.05)	4.8 (0.04)	
Short fiber index (SFI)				
Dryland	11.3 (0.73)	12.3 (0.36)	13.7 (0.81)	
Low	9.3 (0.22)	10.6 (0.42)	11.2 (0.31)	
High	8.8 (0.18)	9.5 (0.41)	10.7 (0.66)	
Upper half mean length (UHML)				
Dryland	1.09 (0.009)	1.07 (0.001)	1.05 (0.007)	
Low	1.15 (0.008)	1.10 (0.005)	1.10 (0.006)	
High	1.15 (0.004)	1.14 (0.006)	1.12 (0.01)	
Uniformity index (UI)				
Dryland	81 (0.3)	80 (0.2)	80 (0.4)	
Low	82 (0.2)	81 (0.3)	80 (0.2)	
High	82 (0.1)	81 (0.3)	81 (0.3)	
Strength (STR)				
Dryland	29 (0.5)	27 (0.1)	26 (0.3)	
Low	30 (0.1)	28 (0.2)	29 (0.2)	
High	30 (0.3)	30 (0.3)	29 (0.2)	
Elongation (ELO)				
Dryland	5.3 (0.02)	5.5 (0.04)	5.3 (0.04)	
Low	5.4 (0.05)	5.4 (0.01)	5.3 (0.02)	
High	5.5 (0.03)	5.4 (0.04)	5.4 (0.06)	

Values in parentheses indicate standard errors. Micronaire: 3.5–3.6 and 4.3–4.9—base, 3.7 to 4.2—premium, and <3.5 and >4.9—discount values; strength (g/tex): 26.0 to 28.9—base, >29.0—premium, and <26.0—discount values; fiber length uniformity: 80.0 to 81.9—base, >81.9—premium, and <80.0—discount values; elongation (%): <5.0—very low, 5.0–5.8—low, 5.9–6.7—average, 6.8–7.6—high, and >7.6—very high.

3.6.2. Short Fiber Index (SFI)

In 2022, the SFI for all cover crop treatments within each irrigation level was outside the optimum range (6 to 9) (Table 6). However, the range from 10–13 is still accepted by cotton consumers. The SFI value of 10.5 was within the range of 10–13 among all treatments across all irrigation levels. In 2023, the SFI values of 8.8 in the low irrigation fallow plot

and 13.7 in the dryland wheat plot (Table 7) were slightly higher than in 2022 but were still within an acceptable range.

3.6.3. Upper Half Mean Length (UHML)

The average length of the longer half of the fibers (UHML) ranged from 1.12 to 1.17, indicating that all our fibers had short fibers in both 2022 (Table 6) and 2023 (Table 7). Increased irrigation levels tended to increase the length of the cotton fiber with high water treatments resulting in the longest fibers, but the overall UHML values were in the lower range of the fiber quality spectrum in both study years regardless of the irrigation treatments.

3.6.4. Uniformity Index (UI)

Uniformity index (UI) values of cotton fibers for dryland, low irrigation, and high irrigation areas were all in the intermediate range (80–82) (Tables 6 and 7). Nevertheless, the irrigation level appeared to have marginally improved the length uniformity.

3.6.5. Strength (STR)

In 2022, the fiber strength values for all treatment combinations were within the range of base values (Table 6). However, in general, the irrigation treatments improved the fiber strength values in 2023, with five of the six irrigation $\times$ cover treatment combinations having fiber strength values in the premium range (Table 7). In 2023, dryland plots also had fiber strength in the lower end of the premium in no-cover treatment (Table 7). In general, cover crops showed no significant impact on fiber strength values.

3.6.6. Elongation (ELO)

Irrigation had a significant influence on fiber elongation. In 2022, fiber elongation (%) was high (7.4) in drylands, high (7.6) to very high (7.7) in low irrigation areas, and very high (7.9–8.0) in high irrigation plots (Table 6). In 2023, the percentages of fiber elongation were low across all treatment combinations (Table 7).

3.7. Correlation between the Number of White Flowers and Lint Yield

Cotton lint was significantly correlated with total white flower densities, but the predictive relationship varied with cotton phenological stages (Table 8). In both years, flower monitoring during the mid-flowering stage (1–17 August; first half of August) could predict lint yield with a high degree of accuracy (2022: $r = 0.82$, 2023: $r = 0.76$) (Table 8). A weak correlation was observed between total early-season white flowers (flowers before 1 August) and fiber yield in both years. Similarly, late-season total white flowers (flowers after 17 August) in 2022 were moderately correlated with the fiber yield ($r = 0.61$) compared to that for 2023 ($r = 0.42$). Total seasonal white flower density was strongly correlated with final lint yield (2022: $r = 0.87$; 2023: $r = 0.79$). It is to be noted that the two-week cumulative white flower densities during the mid-season flowering period (first half of August) were as strongly correlated with final lint yield as total seasonal cumulative flower densities (Table 8). Regression analyses showed that the final lint yield could be reasonably predicted with a simple linear regression equation (Table 9). A normal distribution of residuals and moderate r^2 values of the regression equation parameters for mid-season and seasonal total flower densities (2022: mid-season 0.67, seasonal total 0.76; 2023: mid-season 0.58, seasonal total 0.62) demonstrated a high degree of lint yield predictability via flower density monitoring (Table 9).

Table 8. Pearson correlation coefficient between number of white flowers per hectare at different crop phenological stages and lint yield (kg/ha), 2022–2023.

2022						2023					
Number of White Flowers per Hectare						Numbers of White Flowers per Hectare					
	Early Flowers	Mid Flowers	Late Flowers	Total Flowers	Lint Yield		Early Flowers	Mid Flowers	Late Flowers	Total Flowers	Lint Yield
Early flowers	—				0.31	Early flowers	—				0.38
Mid-flowers		—			0.82	Mid flowers		—			0.76
Late flowers			—		0.61	Late flowers			—		0.42
Total flowers				—	0.87	Total flowers				—	0.79
Lint yield	0.31	0.82	0.61	0.87		Lint yield	0.38	0.76	0.42	0.79	

2022: Early flowers—18–30 July, Mid-flowers—1–17 August, Late flowers—18–26 August; 2023: Early flowers—24–31 July, Mid-flowers—1–17 August, Late flowers—18 August–1 September.

Table 9. Regression coefficients of cotton lint yield (kg/ha) as a function of white flower density (numbers per 1.8 m) at different crop phenological stages, 2022–2023.

Year	Parameter	Early Flowering	Mid Flowering	Late Flowering	Seasonal Total Flowers
2022	Intercept	463.1616	−221.093	304.0832	−294.491
	Slope	7.558491	9.187508	12.16225	6.547101
2023	Intercept	313.6682	−25.5269	310.4632	−87.5675
	Slope	4.555688	6.637253	7.298664	4.327703

Regression Equation $y = mx + b$, where y = lint yield (kg/ha), x = number of white flowers per 1.8 m, m = slope, and b = intercept.

4. Discussion

This study hypothesized that the cover crops would influence the microclimate for thrips colonization in seedling cotton, resulting in reduced thrips injury and/or seedling protection from windstorms, and enhanced plant growth parameters including yield and fiber quality.

The increase in the number of adult thrips in different cover treatments at 21 days after planting (DAP) in 2022 may be attributed to the influx of thrips from drying weeds along the field boundaries. Results for the increased adult thrips density at later seedling stages in 2022 were contrary to Toews et al. [17] who found a decrease in the number of adults at 21 DAP. However, this contrast appeared to be a simple year-to-year variation as the 2023 thrips activity patterns were similar to Toews et al. [17]. It is expected that the adult thrips activity generally declines as seedlings grow and add more true leaves. In our study, immature densities from 14 DAP to 21 DAP declined which is attributed to rain events between the sampling dates. Faircloth et al. (2002) also noted that cumulative rainfall was inversely related to the number of thrips nymphs [21]. In 2023, the number of nymphs increased from 14 DAP to 21 DAP with increased seedling foliage. Also, our study found no significant effect of cover treatments on immature thrips densities which corroborated with Toews et al. [17]. They found no significant difference in thrips densities among three cover crops: rye, wheat, and crimson clover. However, Bowers et al. [22] documented significantly low numbers of thrips nymphs in rye and crimson clover at 21 DAP compared to that on wheat cover. Despite low thrips densities in our study, the density of immature thrips was numerically higher on high irrigation plots at both sampling dates compared to that in dryland plots. The reason for more thrips in irrigated plots may be that irrigation provides favorable microclimate conditions for growing seedlings. The response of early-

season thrips to cover crops and habitat complexity needs further research for a fuller understanding of the plant-environment-insect interactions [23–25].

The thrips injury ranking values were very low in our study in both years. Poor thrips colonization, rain events, and windstorms contributed to overall lower thrips reproduction and insignificant feeding. Also, the ambient temperature increased from 34 °C on 14 DAP to 42 °C for one week which reduced thrips feeding and increased mortality. No significant difference was observed in thrips densities between cover crop plots and fallow plots. As a result, thrips damage to seedlings was also not different between cover and no-cover treatments. The low thrips densities did not allow us to discern the resulting plant damage from thrips feeding injury.

Numerically greater mean plant heights in high irrigation plots in our study are similar to a study that documented an increased plant height by 4.1% with saturated irrigation while deficit irrigation decreased height by 3.2% [26]. In 2023, the impact of irrigation on plant height was more pronounced. The marginal increase in final plant height in sprayed control plots compared to that in thrips-augmented plots can be attributed to plant stress at the early seedlings stage albeit due to low-level thrips injury. One of the previous studies that measured the plant height in July documented that cotton planted on either rye or wheat cover was taller after one year of the study but shorter in the following year [27], which partially supports our results as the plant height was greater in both rye and wheat compared to non-treated plots in both years. By the end of the growing season, cotton planted in wheat was taller, followed by rye and fallow plots in both years. There was no significant difference between wheat and rye, but a significant difference was found between wheat and fallow plots. This result contradicts Li et al. [27], who found cotton planted in no cover crop was taller than that planted in cover crops at the end of the growing season. This might have been due to the differences in the cotton cultivar and cover crops with our study because the response of cotton to cover crops differed according to the genotype used. No significant difference in plant height due to insect treatment was found throughout the growing season, but insect treatment significantly affected plant heights at the end of the growing season in 2022 while no significant difference in plant height at the end of the growing season was observed in 2023.

As expected, flower density was significantly influenced by the amount of irrigation water, with increased water level increasing the flower densities. Our results are consistent with other research reports that found significantly more blooms per unit ground area in irrigated plots than in the dryland plots [28]. Our study also found that plants in irrigated plots had significantly higher flowering rates early in the growing season compared to dryland plots in both years, but this result was contradicted in a two-year study by Pettigrew [22], who found that dryland plots had significantly higher blooming rates compared to irrigated plots. Similar results in moisture deficit conditions were reported for cotton [29]. The greater densities of flowers in water deficit production during the early flowering stage in some studies may be partially explained by the plant's response to water stress triggering the synchronically higher energy allocation in reproductive structures compared to that for vegetative plant growth. The greater rate of flowering in rye and wheat cover plots compared to the fallow plots in our study is likely due to seedling protection from sandstorms and winds that provided the crop earliness. As there was no visible thrips-feeding damage in our study, no apparent variability was observed in the onset of flowering and flowering patterns due to thrips augmentation. This result is consistent with Teague et al. [30], who stated the variability in the onset of flowering was due to thrips injury in the early season. Production of a greater number of flowers on high irrigation regimes aligned with other research that concluded that the increasing irrigation frequency resulted in more flowers [31]. Our results also supported a study that concluded that an increase in flower production due to high soil moisture [32].

The amount of irrigation water correlates with plant growth parameters, flower densities, and lint yield in cotton (Figures 1–8). The low cotton production in dryland is consistent with the results of Schaefer et al. [33] and Delaune et al. [34], who concluded that

the irrigation deficit during primary reproductive development and the early flowering period has negative effects on cotton yield. In our study, continuous water stress in dryland plots might have affected boll formation, within-plant boll distribution, and retention, so the yield obtained was much less compared to high and low irrigation plots. One study found that the use of drip irrigation with a water regime ranging from 4000–4700 m³/ha before sowing at medium plant density (18 plants/m²) produced optimum fiber yield and over-irrigation (5050 m³/ha) or deficit irrigation (3300 or 2950 m³/ha) significantly reduced cotton yield [26]. The water stress effect was mostly seen at the flowering and fruiting stages, resulting in reduced cotton yield in water-deficit production systems, with a more pronounced effect in dryland conditions [35].

Numerically lower yield in rye and wheat plots in both years compared to fallow plots may be partly due to their release of allelochemicals [27]. Most small grain cover crops such as rye and wheat produce allelopathic secondary metabolites that function as natural herbicides. The results of our study are consistent with those of Nayakatawa et al. [36], who observed no significant differences in yield parameters in response to cover crops. Brown et al. [37] and Keeling et al. [38] did not find significant increases in cotton lint yield after planting rye and wheat cover crops. Similarly, one study found cotton lint yield to be less with a no-tillage rye cover crop compared to conventional tillage, which also partly supported our results [39]. The research conducted in a humid environment also found no significant differences among the cover crop treatments influencing cotton yield. Payero et al. [40] reported that any short-term effect of the cover crop on soil water may have been masked by timely rain. However, in our study, there was no timely rainfall that affected soil water content; it may be assumed that the cover crops can extract water from the soil, reducing water availability for the succeeding main crop. The needed nutrients for the main crop following the cover crop may have been retained in the cover residues as the rye cover crop was still standing in the field after it had been terminated after cotton planting.

A strong correlation between flower densities and lint yield shown in our study can be a useful predictive tool in cotton production input management. While a very strong correlation was observed between mid-season flower densities and yield as well as seasonal total flower densities and lint yield, early and late-season flower densities also provided a satisfactory correlation with lint yield. In fact, one-week cumulative flower densities appeared to provide a reasonable estimate of the resulting lint yield.

Various fiber quality parameters were impacted by irrigation × cover crops × thrips augmentation treatment interactions. Our results showed that the increased value of micronaire in moderate water deficit conditions. This type of result with the increased value of micronaire during moderate water deficit was also found by Pettigrew [28], Balkcom et al. [41], and Dagdelen et al. [42]. Zhang et al. [26] found that irrigation level did not have a significant effect on fiber quality. Deficit irrigation increased micronaire, which is consistent with the results of our study. Similarly, the decreased value of micronaire as irrigation increased was reported by many researchers [43–45]. Some research showed that irrigation increased micronaire by 11% for two consecutive years but decreased micronaire by 4% in another year [28], partly supporting our results. The significant influence of water stress has been reported by Karademir et al. [35] which contradicts our results where they showed significant differences between water-stressed and non-stressed plots. However, the average fiber fineness values obtained from the stressed plot was 4.07 mic, and the non-stressed plot was 4.41 mic which agrees with our results. Unlike the research results mentioned above, another study revealed that growing cotton under non-irrigated conditions resulted in reduced micronaire [46]. The water stress during the mid-bloom stage resulted in increased micronaire compared to non-stressed plots [47]; however, some research reported reduced micronaire under non-irrigated conditions [35]. Booker et al. [2] reported that the micronaire was not affected by irrigation rate, suggesting that micronaire values are influenced by complex interactions of irrigation water availability and other environmental and input variables than irrigation water alone. Several researchers noted that the cover crops influenced fiber maturity and fiber fineness (micronaire values) as we

observed in our study [48]. Donald et al. [49] found that micronaire increased in no-tillage wheat winter cover compared to that in conventional tillage with no cover, suggesting that the earlier boll development resulted from greater heat unit accumulation and a more mature cotton fiber may have been produced due to the benefits of no-tillage systems. Schomberg et al. [50] found that the micronaire values were better in the non-grazed treatment of winter rye compared to grazed winter rye in cotton. The non-grazed winter rye treatment means the rye cover crop was still in the field, which is similar to the status of the rye cover crop in our study until it was terminated 27 days before the cotton was planted. The micronaire value was lower than 0.1 units following rye cover than following legumes in one study, and the value following winter fallow was intermediate between rye and the legumes. These values are significant for rye versus legumes, where it was found that cotton yield following rye cover crop has the greatest yield in conservation tillage without affecting fiber quality [51]. Unlike our results, the short fiber index (SFI) was significantly influenced by cover crops [48]; however, they stated the difference observed was not sufficient to justify practical and economic concerns. Other studies have reported no effects of cover crops on SFI [51–53]; these results align with our study. The non-grazed treatment of rye in cotton fields was found to have better properties compared to the grazed treatment of rye [50].

5. Conclusions

The adoption of cover crops in agroecosystems should be made with the consideration of whether the cover crop water usage reduces the cash crop water usage efficiency. Producers should also be aware of how a cover crop alters the water dynamics over wetter and drier seasons to evaluate their benefits. Despite the increase in cotton height and the total number of flowers in rye and wheat compared to fallow plots, the fiber yields were not significantly improved in plots with cover crops compared to fallow. However, the irrigation treatment significantly influenced cotton yield, where high irrigation plots resulted in significantly more yield than low and dryland plots. No significant differences in cotton yields were found between thrips-treated plots and non-infested control plots throughout this study due to the lack of significant thrips injury even after artificial augmentation of thrips in both years. The weather anomalies in the years 2022 and 2023 that were responsible for uncharacteristically low thrips densities, as well as insignificant thrips that make it challenging to discern the plant response to environmental and input variables, warrant a more thorough investigation of multi-year, multi-location ecological studies to characterize physiological aspects of plant response to these interactions.

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