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ENGINEERING AND GINNING

Experimental Thermal Defoliator Trials

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ABSTRACT

Rules for organic labeling restrict the use harvest-aid chemicals. This study was conducted to determine whether thermal defoliation as an alternative to harvest-aid chemicals could prepare cotton for harvest without damaging fiber and seed quality. Untreated and standard chemical defoliant control treatments were compared with thermal treatments that consumed propane at rates less than 93.5 L/ha (10 gal/a), between 93.5 (10) and 140.0 L/ha (15 gal/a), and more than 140.0 L/ha (15 gal/a). The experimental defoliator forced hot air through two cultivars of cotton (Acala 1517-99 and Deltapine 565) that were grown on a Brazito fine sandy loam and on a Harkey clay loam. For three of the four plant/soil combinations that were evaluated, the medium and high levels of thermal defoliation resulted in over 90% leaf kill within 7 d. For Deltapine 565, the high thermal treatment resulted in a $0.03/kg gain in fiber value over the untreated control. For Acala 1517-99, high thermal treatment added $0.10/kg. For both cultivars, there were few significant differences in yarn quality measures.

Mechanization of cotton harvesting began in the late 1940s, and by the mid 1960s nearly all cotton in the United States was mechanically harvested. Since that time, harvest-aid chemicals have been introduced to facilitate mechanical harvesting. Three types of harvest-aid chemicals are available that each have a distinct purpose; 1) defoliants that cause the plant to drop leaves; 2) desiccants that cause plant material to wither and dry; and 3) boll openers, which have been developed more recently, that stimulate the opening of physiologically mature green cotton bolls.

Proper use of harvest-aid chemicals can improve harvest efficiency. Green leaves that remain attached to the stalk can interfere with access of the lint to the spindles on the harvester, which can lead to lower harvest efficiencies, because some cotton is left in the field. Plant juices in green leaves tend to gum-up picker spindles, resulting in downtime for cleaning, which leads to delays in harvesting.

The use of harvest aid chemicals can also improve fiber quality. During the harvesting process, fiber is rubbed against green leaves that remain on the plant. Chlorophyll in these leaves stains the fiber, which lowers price grades. High levels of leaf trash also reduce lint value. Delaying harvest until a hard frost kills the leaves and eliminates chlorophyll stains, but prolongs the fiber's exposure to weather and to honeydew from late season sucking insects, which reduces yields and lint value.

Producers growing organic cotton are restricted from using harvest-aid chemicals (Merrigan, 2000). Furthermore, chemical usage is restricted 3 yr prior to the production of any crop labeled "organic," so restrictions apply to cotton if it is grown in rotation with any organic crop. These laws also apply to adjoining land, if buffer zones and runoff diversions cannot prevent the unintended application of prohibited substances to organic cropland. Therefore, alternatives to chemical defoliation are needed. Thermal defoliation could be a viable means for organic producers to terminate their cotton crop for a more timely harvest, greater harvest efficiency, and reduced fiber quality degradation.

Thermal defoliation of cotton was first described by Nisbet and Nisbet (1954), first practiced by Kent and Porterfield (1967), and subsequently demonstrated in several states (Batchelder et al., 1971). Hot air treatment using an oven-like device transported through the field resulted in 80% defoliation (Porterfield and Batchelder, 1969). Fuel costs associated with thermal defoliation were equivalent to the cost of chemical defoliants. Complete desiccation was achieved by burning 93.5 L of propane per hectare

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(10 gal/a) (Wheeler and Ford, 1974). The capital cost of a single-purpose machine requiring complex controls was seen as a barrier to its widespread application in the 1970s.

Interest in thermal defoliation has been rekindled with the increase in organic cotton production. Secondary benefits that arise from thermal defoliation include control of late season sucking insects responsible for stickiness, harvest preparation that is less dependent on weather conditions, and the potential for immediate harvest. Technological advances in electronic controls and other developments could mitigate capital cost issues that were seen as a hindrance in the 1970s. The premium paid for organic cotton could mitigate application costs, as fuel costs associated with thermal defoliation are still equivalent to the cost of chemical defoliants.

Recent thermal defoliation research using superheated steam was shown to be effective, but the mass of the boiler and feed water tank, along with the need for deionized water, limited the application (Funk et al., 2001). Later, hot air was successfully used for cotton defoliation (Funk et al., 2002). Thermal defoliation experiments using hot air were tested in Las Cruces, NM., Five Points and Shafter, CA, and Lubbock, TX. A one-row experimental thermal defoliator was constructed and evaluated to determine the technical and economic feasibility of thermal defoliation. Quantified parameters include fuel consumption, harvest efficiency, defoliation, leaf kill, and fiber and yarn quality measures.

MATERIALS AND METHODS

According to the literature (Porterfield et al., 1970) and J. G. Porterfield (personal communication), the thermal defoliator patent holder and one of the principal investigators from the trials conducted during 1960s, a limitation of early thermal defoliator prototypes was field efficiency. For these early prototypes a slow ground speed was required for heat to transfer into the cotton canopy. Attempts to increase ground speed by raising the temperature above 200°C (392°F) resulted in fiber damage (scorching). One of the objectives for the design of this experimental thermal defoliator was to improve heat transfer without exceeding 200°C (392°F). Convective heat transfer is a function of fluid velocity, as well as temperature differential, so forcing high speed air through the cotton canopy was expected to permit an increase defoliator ground speed.

Laboratory trials with potted plants confirmed that 12.4 m/s (2450 fpm) was an acceptable air velocity for treatment. The experimental defoliator used 576 nozzles that were 2.54 cm (1.0 in) in diameter to force air through the canopy. Figure 1 illustrates the design of the treatment chamber in a cross sectional view. Nozzles line the top and left side of the 61 x 61 cm (24 x 24 in) tunnel. The 3m (10 ft) long treatment tunnel forced hot air in from one side of the row in the front half, and from the other side in the rear half. This configuration resulted in a uniform thermal treatment across the width of the plant.

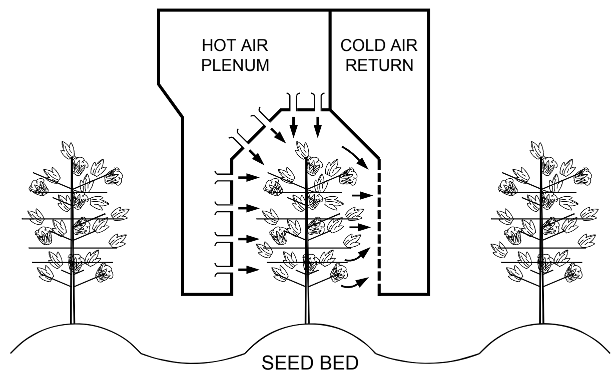

Figure 1. Cross-section of diagram of the experimental thermal defoliator indicating the paths of air flow.

Perforated metal was used on the side of the treatment tunnel opposite the nozzles to provide a return air path. This design improved air penetration through the canopy and recovered some heat by recirculating the warm air. A 4.25 m^3/s (9,000 cfm) fan powered by a 11.2 kW (15 hp) hydraulic motor supplied a mixture of approximately 33% fresh and 67% recirculated air to a 732 kW (2.5 MBTU/hr) propane fired burner. Propane was supplied from a 3785 L (1000 gal) tank secured to a trailer. The trailer was towed behind the tractor on access alleys, while the experimental defoliator was towed through the research plots by a tractor with a toolbar projecting to one side (Fig. 2).

A temperature controller and burner safety interlock devices were located in an electrical enclosure above a data logger. A 12 V direct current battery and inverter provided 110 V alternating current to power the data logger, the propane safety solenoids (two pilot and two main), the high and low gas pressure and fan pressure switches, an over-temperature protection relay, the proportional-integral-derivative temperature controller, and the control valve actuator.

Figure 2. Experimental thermal defoliator.

Wheels supported the experimental thermal defoliator on 1.0 m (40 in) centers, a typical row spacing used by producers in the test area. Crop dividers helped guide the cotton into the treatment chamber without dislodging cotton from open bolls. Before being returned to the tractor hydraulic PTO through quick disconnect fittings, hydraulic oil turning the fan motor was cooled in a small radiator attached to the fresh air intake. A hydraulic cylinder on the toolbar attached to the three-point hitch of the tractor was used to position the experimental defoliator over either the outer row (closest to the tractor) or second row adjacent to access alleys (Fig. 2). The access alleys were made by leveling three unplanted rows between every four planted rows across the width of the field (Fig. 3).

The data logger recorded treatment air temperatures from 12 locations in the treatment tunnel. It also recorded fan speed, fan pressure, return air temperature, and ambient air temperature. Values were stored at 1 s intervals. The mean of all these values was hand recorded for each row, along with the starting and ending time and gas meter readings. Mean dwell time per treatment, propane fuel consumption per area, and area covered per hour were calculated using row length and mean values. Results from the two rows that made up each plot (or replicate) were then averaged.

Two cultivars, Delta Pine 565 and Acala 1517-99 (Delta Pine and Land Co.; Scott, MS), were randomly assigned to 18 paired plots. Each plot consisted of an inner and outer row running the length of the field. Three rows were skipped between each paired two-row plot to served as access alleys. The field was

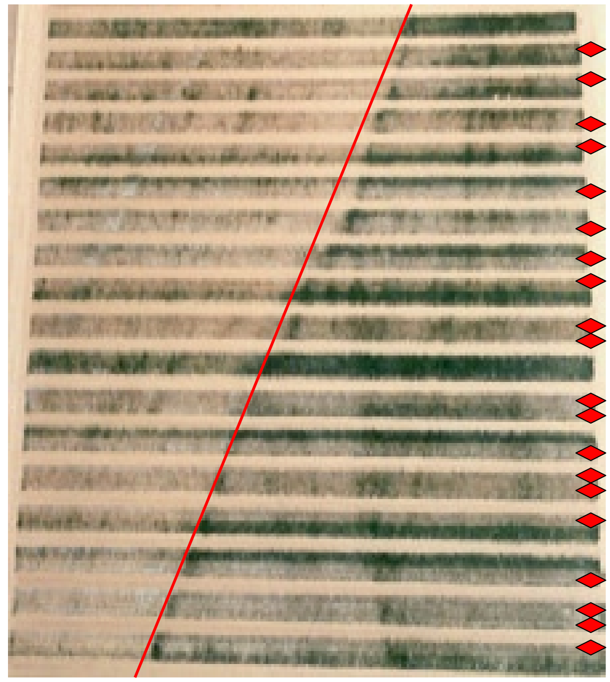

Figure 3. Aerial photo taken 3 d after treatment. Brazito fine sandy loam at left, Harkey clay loam at right. Leaf kill (lighter color) is evident in thermal treatment plots (indicated with red diamonds). Tan strips are access alleys between plots.

furrow irrigated at approximately 2 wk intervals uniformly throughout the growing season. The entire field was treated as one unit with mepiquat chloride (Pix; BASF Corp.; Research Triangle Park, NC) on 2 and 29 July, prometryn (Caparol 4L; Syngenta Crop Protection; Greensboro, NC) on 17 July, and pink bollworm pheromone (Checkmate PBW-W, Suterra LLC; Bend, OR) on 8 Aug. The boll weevil eradication program scheduled aerial applications of malathion as needed.

The field had two distinct soil types. One end of the field was a Brazito fine sandy loam (mixed, thermic, Typic Torripsamment) and the other end was a Harkey clay loam (coarse-silty, mixed, superactive, calcareous, thermic Typic Torrifluvent). Differences in soil type affected available moisture during the growing season and resulted in differences in final plant sizes and architectures. At the Brazito end of the field, plants were less than 1.0 m (40 in) high and had openings in the canopy between each row. At the Harkey end, plants were over 1.5 m (59 in) and the canopy bridged the furrows between rows. Also, cotton grown in the Harkey soil had more vegetative growth than cotton grown in the Brazito soil. Unfortunately, the border between the two soil types ran diagonally (Fig. 3), so subplots were not uniform in area. This introduced uncertainty concerning yield estimates.

Two control treatments were included in the study. A chemical defoliant control consisted of a tank mix of ethephon and cyclanilide (Finish 6 at 2.34 L/ha; Bayer CropScience; Research Triangle Park, NC) and thidiazuron and diuron (Gin Star EC at 0.51 L/ha; Bayer CropScience) applied to two plots of each cultivar. Three plots of each cultivar received no defoliation treatment (untreated check, or 'green' treatment). Thermal defoliation treatments were applied at three levels; low, medium, and high. The high defoliation treatment used more than 140.0 L (15 gal), medium used between 104.0 L (15 gal) and 93.5 L (10 gal), and low used less than 93.5 L (10 gal) of propane per acre. Fuel consumption was a function of treatment time and temperature (Funk et al., 2003).

Defoliation treatments were initiated 28 d after the last irrigation. Although cotton grown at the Brazito end of the field exhibited initial signs of leaf kill and defoliation, cotton grown at the Harkey end did not exhibit either. There appeared to be residual moisture in the soil at the Harkey end, enabling plants to sustain growth even after defoliation treatments had been applied. Regrowth, seldom a problem in irrigated cotton production, was not quantified. Plots were harvested 29 d after defoliation.

The percentage defoliation and leaf kill was determined by selecting and flagging one representative cotton plant from each soil type and row for all plots. The plant selection process resulted in two flagged plants (observations) within the Brazito soil area and two in the Harkey soil area of each replicate. The number of green and brown leaves on each plant was counted and recorded just before treatment and 7, 14, and 21 d after treatment (DAT). Percentage defoliation was calculated by comparing the total number of leaves remaining on each plant at the time of the observation with the number of leaves on the plant before treatment. Leaf kill was calculated by comparing the number of green leaves remaining on each plant at the time of the observation with the number of leaves on the plant before treatment. Missing leaves were presumed dead.

Each plot was harvested and kept separate to make one ginning lot. Each lot was ginned separately at the USDA-ARS-Southwestern Cotton Ginning Research Laboratory in Mesilla Park, N.M. Initial lot weights were used to estimate yield and turnout. Two inclined cleaners and one burr-stick machine removed foreign matter prior to saw ginning, and two stages of saw-type lint cleaning removed foreign matter before the bale press. Foreign matter was collected and weighed from each processing machine so that accurate estimates of lint turnout could be calculated. Two replicate seed cotton samples were collected at the trailer and at the gin stand feeder apron to evaluate pre-cleaning effectiveness. Foreign matter content in the seed cotton was determined by the fractionation method (Shepherd, 1972). Two replicate lint samples were taken before the first and second lint cleaner and before the bale press to evaluate lint cleaning effectiveness. Foreign matter content in the lint was determined by the Shirley Analyzer (SDL America Inc., Charlotte, NC) (ASTM, 1996a).

Additional pairs of samples were taken before the bale press for fiber analysis. Cotton classification, as determined from high volume instrumentation (HVI), was conducted by the USDA-AMS Classing Office in Phoenix, Ariz. Two replicate seed samples were collected as each lot was ginned. Cottonseed germination testing was performed by the State Seed Laboratory at New Mexico State University in Las Cruces, using standard methods (AOSA, 2003).

Two lots separated by paper were combined into a bale for shipping to the USDA-ARS Cotton Quality Research Unit (CQRU) in Clemson, SC, where lots were separated and weighed. At CQRU, strength and elongation were determined by the Stelometer test (ASTM, 1996b), and length, length uniformity, and length distribution by the Fibrograph (ASTM, 1996c) and Peyer (ASTM, 1996d) tests. Other fiber properties were quantified at CQRU using an Advanced Fiber Information System (AFIS).

Yarn properties were determined at CQRU on 20/1 carded yarn. Opening and carding were done on a Truetzschler cleaning line and 803 card, producing a 60 grain sliver at 46 kg/h (100 lb/h). Spinning was done on an open end spinning frame. The yarn was spun at 100,000 rpm rotor speed and 3.75 T.M. yarn twist.

The GLM procedure in SAS (SAS Institute; Cary, NC) was used to conduct analysis of variance and Duncan's multiple range test to separate means ($P \leq 0.05$) grouped by cultivar and treatment. Treatment was considered a class variable. The high thermal treatment, over 140 L/ha (15 gal/a) of propane, was replicated three times per cultivar. The medium thermal treatment, from 93 to 140 L/ha (10 to 15 gal/a) of propane, had seven replicates per cultivar. And the low thermal treatment, less than 93 L/ha

(10 gal/a) of propane consumed, also was replicated three times in each cultivar. The chemical treatment standard was replicated two times in each cultivar and the untreated "Green" check was replicated three times in each cultivar. For the plant responses (Table 1), leaves were counted on one plant in each row at each end of the field, for a total of two observations for each replicate and soil type. A two-row picker harvested cotton from the entire length of the field (one plot) into one ginning lot; therefore the analysis of fiber and yarn properties can not examine the effect of soil type (Tables 2 through 9).

Table 1. Percentage defoliation and leaf kill at 7, 14, and 21 days after defoliation (DAT) by cultivar and soil type

Cultivar and soil type	Treatment [y]	Defoliation (%)			Leaf kill (%)		
		7 DAT	14 DAT	21 DAT	7 DAT	14 DAT	21 DAT
Acala 1517-99							
Brazito very fine sandy loam							
	Chemical	52 a [z]	91 a	94 a	52 b	96 a	99 a
	Green	18 bc	38 bc	57 a	22 c	40 b	63 b
	Low	39 abc	60 b	76 a	73 ab	83 a	92 a
	Medium	42 ab	55 b	70 a	96 a	95 a	99 a
	High	13 c	28 c	53 a	99 a	100 a	100 a
	P	0.0309	0.0025	0.0554	<0.0001	0.0002	0.0002
Harkey clay loam							
	Chemical	41 a	59 a	67 a	41 b	59 a	79 a
	Green	-11 b	0 b	18 b	-11 c	0 b	19 b
	Low	-4 b	13 b	27 b	-3 c	15 b	31 b
	Medium	48 a	66 a	76 a	69 ab	80 a	83 a
	High	54 a	77 a	79 a	85 a	89 a	89 a
	P	0.0002	0.0004	0.0003	0.0002	<0.0001	0.0003
Delta Pine 565							
Brazito very fine sandy loam							
	Chemical	49 a	83 a	85 a	51 c	87 ab	92 a
	Green	26 a	41 b	56 a	28 d	43 c	70 a
	Low	42 a	59 ab	69 a	68 b	74 b	74 a
	Medium	24 a	45 b	59 a	100 a	100 a	100 a
	High	35 a	48 b	55 a	100 a	100 a	100 a
	P	0.0787	0.0431	0.2363	<0.0001	<0.0001	0.0594
Harkey clay loam							
	Chemical	47 a	78 a	87 a	47 b	78 ab	89 ab
	Green	-4 b	6 b	29 b	-3 c	7 c	31 c
	Low	44 a	58 a	63 a	56 b	61 b	67 b
	Medium	53 a	71 a	78 a	90 a	90 ab	94 a
	High	43 a	70 a	80 a	100 a	100 a	100 a
	P	0.0018	<0.0001	0.0034	<0.0001	<0.0001	<0.0001

[y] Chemical treatment was (2.34 L/ha Finish and 0.51 L/ha Gin Star) and the green treatment was the untreated control. Low, medium, and high were the experimental thermal treatments that used more than 140 L (15 gal), 93.5 to 140 L (10 to 15 gal), and less than 93.5 L (10 gal) of propane per hectare, respectively.

[z] Means with in the same column for a soil type and cultivar followed by the same letter are not statistically different according to Duncan's multiple range test ($P \leq 0.05$) .

Fiber value was calculated using 2002 USDA loan values (USDA-FSA, 2002) and Cotton Loan 2002 software (Falconer, 2002). Propane price calculations were based on the El Paso refinery spot price, plus transportation and distribution in Sept. 2002. The total was $0.32/L ($1.20/gal).

RESULTS AND DISCUSSION

Due to the affect soil type (and plant response to soil type) had on leaf kill and defoliation following thermal and chemical treatments, results are presented separately for plants grown in each soil (Table 1).

At 7 DAT, the green treatment had the lowest leaf kill. In the Harkey clay loam, untreated plants set additional leaves, which resulted in negative leaf kill numbers. At 7 DAT, medium and high thermal treatments had a significantly higher percentage of leaf kill than the other treatments. Leaf kill was over 90% for Acala 1517-99 on the Brazito soil and for Deltapine 565 on both the Brazito and Harkey soils. The fact that leaf kill was over 90% at 7 DAT with thermal defoliation is perhaps the most significant finding of this investigation. Cotton can be harvested when leaf kill is over 90%; therefore, a more timely harvest is possible with thermal treatment than with chemical treatment.

Defoliation of Acala on Brazito soil at 7 and 14 DAT was less than the chemical control even though leaf kill was greater. In dry soil, chemical treatment resulted in greater levels of defoliation than the high thermal treatment the first 2 wk. Higher levels of thermal treatment appeared to "stick" the leaves, like a hard frost, but leaf kill was very rapid.

At 14 DAT, leaf kill from the medium and high thermal treatments was not statistically different from the standard chemical treatment on both soil types for both cultivars. For both cultivars, on Harkey soil defoliation percentages at 14 DAT were not significantly different among the medium and high thermal treatments and the chemical treatment, but on Brazito soil the chemical treatment resulted in a significantly higher defoliation percentage at14 DAT.

At 21 DAT, leaf kill and defoliation percentage on both soil types were not statistically different between the chemical and the medium and high thermal treatments. These results demonstrate that leaf kill and defoliation using heat or chemical defoliants are similar after a sufficient period of time (21 DAT).

Cotton treated with chemicals or heat improved seed germination compared with the green control treatment (Table 2). The seed was inside a lock of lint, if not a closed boll, at the time the treatments

Table 2. Effect of defoliation treatments on the percentage of seed germination, foreign matter content, and number of neps

Cultivar	Treatment [y]	Seed germination (%)	Foreign matter (%) Seed cotton Wagon	Foreign matter (%) Seed cotton Feeder	Foreign matter (%) Bale lint	Foreign matter (%) Seed	Neps (g^{-1})
Acala 1517-99							
	Chemical	66 ab [z]	8.3 ab	3.2 a	3.4 a	0.45 a	329 a
	Green	48 c	7.3 b	3.4 a	3.2 a	0.47 a	306 a
	Low	61 b	9.1 a	3.5 a	3.3 a	0.43 a	322 a
	Medium	76 a	9.8 a	3.3 a	3.0 a	0.46 a	329 a
	High	77 a	8.6 ab	3.5 a	2.9 a	0.36 a	339 a
	P	0.0003	0.0157	0.7300	0.1673	0.7184	0.2890
Delta Pine 565							
	Chemical	72 b	6.8 b	1.8 a	1.7 ab	0.39 a	291 a
	Green	68 c	8.1 b	2.3 a	1.8 a	0.36 a	283 a
	Low	75 ab	7.8 b	1.9 a	1.7 ab	0.43 a	274 a
	Medium	76 a	7.8 b	1.8 a	1.6 b	0.41 a	305 a
	High	75 ab	10.0 a	2.0 a	1.6 b	0.38 a	314 a
	P	0.0005	0.0077	0.2209	0.0293	0.7178	0.4131

[y] Chemical treatment was (2.34 L/ha Finish and 0.51 L/ha Gin Star) and the green treatment was the untreated control. Low, medium, and high were the experimental thermal treatments that used more than 140 L (15 gal), 93.5 to 140 L (10 to 15 gal), and less than 93.5 L (10 gal) of propane per hectare, respectively.

[z] Means with in the same column for a cultivar followed by the same letter are not statistically different according to Duncan's multiple range test ($P \leq 0.05$) .

were applied, so it is difficult to ascribe germination differences directly to treatment affects.

There were some differences in the amount of foreign matter arriving at the cotton gin (wagon), but the seed cotton cleaning equipment eliminated all statistically significant differences by the time the cotton entered the gin stand (Feeder). Nep count in ginned fiber was not significantly different among treatments (Table 2).

Color grade quantified by the USDA-AMS Classing Office in Phoenix was converted to the classing code used in the 1960s, because this older code is linear and continuous, which facilitated statistical analysis. Color grade was significantly improved with medium and high thermal treatments for the Acala cultivar (Table 3). For the Deltapine cultivar, thermal treatments were not statistically different from the chemical standard. All other HVI measures were not affected by defoliation treatment.

Medium and high thermal and chemical treatments improved HVI reflectance and yellowness compared with untreated cotton, but there were no differences among chemical and the medium and high thermal treatments (Table 4). There were no significant differences between treatments for the other fiber quality parameters. There were no significant differences between defoliation treatments for fiber quality parameters measured with AFIS (Table 5).

Compared with the chemical treatment, the high level of thermal defoliation reduced mill waste in the opening and cleaning operation for Acala, and improved mill efficiency (reduced ends-down per thousand hours) for Deltapine (Table 6). Thicks per thousand meters (Table 7) were reduced by thermal treatment compared with the chemical treatment for the Deltapine cultivar, but not for the Acala cultivar. Treatment also had an impact on irregularity for both cultivars (Table 8). All other open-end spinning yarn properties were unaffected by defoliation treatment type.

Observed yields were not reliable for analysis due to poor randomization. Two replicates for the chemical treatment came from the longest plots on the Brazito fine sandy loam soil (Fig. 3, top), which produced lower yields than the Harkey clay loam. Differences in yield were most likely due to soil type rather than treatment effects. Therefore, average

Table 3. Effect of defoliation treatments on USDA-AMS classing office high volume instrument measures of color, leaf, micronaire, length, staple, strength, and uniformity

Cultivar	Treatment [x]	Color grade [y]	Leaf grade	Micronaire	Length (cm)	Staple length ($in\ 32^{-1}$)	Strength ($cN\ tex^{-1}$)	Uniformity (%)
Acala 1517-99								
	Chemical	91.5 b [z]	4.8 a	43 a	116 a	37 a	30.1 a	82 a
	Green	89.0 c	5.0 a	43 a	118 a	38 a	31.6 a	82 a
	Low	89.0 c	4.5 a	43 a	118 a	38 a	30.9 a	82 a
	Medium	93.6 a	4.2 a	43 a	117 a	37 a	31.2 a	82 a
	High	94.0 a	4.3 a	43 a	117 a	37 a	31.7 a	82 a
	P	<0.0001	0.0665	0.9622	0.1856	0.3003	0.8186	0.0602
Delta Pine 565								
	Chemical	97.0 ab	2.3 a	47 a	115 a	37 a	28.9 a	81 a
	Green	94.0 b	2.7 a	46 a	116 a	37 a	28.4 a	81 a
	Low	94.0 b	2.0 a	46 a	115 a	37 a	26.6 a	81 a
	Medium	98.3 a	2.1 a	46 a	116 a	37 a	28.1 a	81 a
	High	99.0 a	2.2 a	46 a	115 a	37 a	28.3 a	81 a
	P	0.0046	0.0951	0.8462	0.6624	0.4510	0.2770	0.0876

[x] Chemical treatment was (2.34 L/ha Finish and 0.51 L/ha Gin Star) and the green treatment was the untreated control. Low, medium, and high were the experimental thermal treatments that used more than 140 l (15 gal), 93.5 to 140 L (10 to 15 gal), and less than 93.5 L (10 gal) of propane per hectare, respectively.

[y] Converted to USDA-AMS classing code from the 1960s to facilitate statistical analysis.

[z] Means with in the same column for a cultivar followed by the same letter are not statistically different according to Duncan's multiple range test ($P \leq 0.05$) .

Table 4. Effect of defoliation treatments on USDA-AMS classing office high volume instrumentation (HVI) color reflectance and yellowness, Stelometer strength and percentage elongation, and Fibrograph 2.5% span length and percentage uniformity ratio

Cultivar	Treatment [y]	HVI		Stelometer		Fibrograph	
		Reflectance (Rd)	Yellowness (+b)	Strength (cN tex^{-1})	Elongation (%)	Span length (cm)	Uniform ratio (%)
Acala 1517-99							
	Chemical	71 ab [z]	86 b	23.5 a	6.2 a	.047 a	45.3 a
	Green	69 c	93 a	23.5 a	6.4 a	.046 a	44.3 a
	Low	70 bc	90 a	23.5 a	6.1 a	.047 a	45.0 a
	Medium	73 a	84 b	22.6 a	6.3 a	.046 a	44.9 a
	High	73 a	84 b	22.6 a	6.3 a	.046 a	43.8 a
	P	0.0015	0.0010	0.3387	0.4724	0.1068	0.1460
Delta Pine 565							
	Chemical	77 a	76 c	20.6 a	7.0 a	.046 a	43.3 a
	Green	75 c	81 a	20.6 a	6.9 a	.046 a	44.2 a
	Low	76 b	79 ab	20.6 a	6.7 a	.045 a	43.7 a
	Medium	77 a	78 bc	20.6 a	6.8 a	.045 a	43.6 a
	High	77 a	77 bc	19.6 a	7.0 a	.045 a	44.0 a
	P	<0.0001	0.0019	0.4800	0.5374	0.1385	0.3909

[y] Chemical treatment was (2.34 L/ha Finish and 0.51 L/ha Gin Star) and the green treatment was the untreated control. Low, medium, and high were the experimental thermal treatments that used more than 140 L (15 gal), 93.5 to 140 L (10 to 15 gal), and less than 93.5 L (10 gal) of propane per hectare, respectively.

[z] Means with in the same column for a cultivar followed by the same letter are not statistically different according to Duncan's multiple range test ($P \leq 0.05$) .

yield for each cultivar and fiber value was used to calculate gross return per hectare (Table 9). Thermal treatment at the high and medium levels resulted in a better price for the Acala cultivar because of higher color grades (Table 3). Since there was little difference in color grades for the Deltapine cultivar (Table 3), fiber value was not different. Subtracting chemical and chemical application costs resulted in a baseline net return (ignoring all other production costs). This was compared with the net return obtained when subtracting propane fuel costs (again, ignoring all other production costs, AND the application cost of the thermal treatments.) Because actual production costs were not available, and because the single-row experimental thermal treatment device used in these trials is not a good predictor of application costs, this version of difference in net return is presented as a means of comparing defoliation treatments.

Many variables must be assumed when estimating expenses associated with applying thermal treatments. Therefore, net return difference values presented in Table 9 do not include the cost of labor and machinery associated with thermal treatment, but only fuel. Subtracting the fuel portion of the cost of each thermal treatment and the total cost of chemical treatment (labor, machinery and chemicals) from the value of the fiber produced per area provided an estimate of the amount that could be spent for labor and machinery for thermal defoliation to cost no more than chemical defoliation. Using 2002 prices, the maximum difference in net return between chemical and medium or high thermal defoliation was \$137/ha (\$55/acre) for Acala 1517-99 and \$58/ha (\$23/acre) for Deltapine 565. These differences reflect the economic limit for thermal defoliation to cost the same as chemical defoliation. Another agricultural operation involving expensive machinery and low ground speeds is custom harvesting. The cost of custom harvesting might be somewhat predictive of the labor and machinery cost of custom thermal defoliating, if this industry should develop. The price range custom harvester companies charge for picking cotton is \$247 to \$272/ha (\$100 to \$110/ac), including labor for forming and covering the modules. For small grains the range is \$44 to \$74/ha (\$18 to \$30/ac), which includes trucking the grain.

Table 5. Effect of defoliation treatments on advanced fiber information system (AFIS) mean length, coefficient of variation, percentage of short fiber (under 1.27 cm) and very short fiber (VSF; under 0.64 cm), upper 25% length (exceeded by 25% of the fibers by number)

Cultivar	Treatment [y]	AFIS				
		Mean length (cm)	C.V. (%)	Short fiber (%)	U 25% length (cm)	VSF (%)
Acala 1517-99						
	Chemical	0.37 a [z]	31 a	7.9 a	0.46 a	0.80 a
	Green	0.38 a	31 a	7.5 a	0.46 a	0.63 a
	Low	0.37 a	31 a	7.8 a	0.46 a	0.63 a
	Medium	0.37 a	32 a	8.2 a	0.46 a	0.94 a
	High	0.37 a	31 a	7.4 a	0.46 a	0.75 a
	P	0.4203	0.8088	0.7998	0.4863	0.7366
Delta Pine 565						
	Chemical	0.37 a	32 a	8.6 a	0.45 a	0.75 a
	Green	0.37 a	32 a	9.0 a	0.45 a	0.93 a
	Low	0.36 a	33 a	9.7 a	0.45 a	0.95 a
	Medium	0.36 a	33 a	10.3 a	0.45 a	1.29 a
	High	0.36 a	33 a	9.8 a	0.44 a	0.87 a
	P	0.3827	0.7025	0.6390	0.3984	0.5339

[y] Chemical treatment was (2.34 L/ha Finish and 0.51 L/ha Gin Star) and the green treatment was the untreated control. Low, medium, and high were the experimental thermal treatments that used more than 140 L (15 gal), 93.5 to 140 L (10 to 15 gal), and less than 93.5 L (10 gal) of propane per hectare, respectively.

[z] Means with in the same column for a cultivar followed by the same letter are not statistically different according to Duncan's multiple range test ($P \leq 0.05$) .

Table 6. Effect of defoliation treatments on mill waste, mill efficiency, actual yarn size, yarn strength, and coefficient of variation for strength

Cultivar	Treatment [y]	Open-end spinning					
		Opening/ cleaning waste (%)	Card waste (%)	Ends down (kh^{-1})	Yarn size obtained (Ne)	Strength ($cN\ tex^{-1}$)	Strength C.V. (%)
Acala 1517-99							
	Chemical	1.75 a	2.5 a	166	19.6 a	11.8 a	9.1 a
	Green	1.71 a	2.4 a	407	19.7 a	11.9 a	9.6 a
	Low	1.76 a	2.5 a	209	19.9 a	11.6 a	9.5 a
	Medium	1.63 ab	2.5 a	317	19.8 a	11.9 a	8.8 a
	High	1.56 b	2.5 a	310	19.8 a	11.9 a	9.3 a
	P	0.0449	0.9964	0.2189	0.1141	0.5170	0.3657
Delta Pine 565							
	Chemical	1.11 a	1.8 a	264 a	19.8 a	11.0 a	8.7 a
	Green	1.18 a	1.9 a	250 ab	19.7 a	10.7 a	9.2 a
	Low	1.12 a	1.8 a	139 bc	19.5 a	10.9 a	8.2 a
	Medium	1.18 a	1.9 a	105 c	19.6 a	10.8 a	8.5 a
	High	1.13 a	1.8 a	88 c	19.7 a	10.9 a	8.8 a
	P	0.6113	0.3740	0.0125	0.4062	0.6395	0.3305

[y] Chemical treatment was (2.34 L/ha Finish and 0.51 L/ha Gin Star) and the green treatment was the untreated control. Low, medium, and high were the experimental thermal treatments that used more than 140 L (15 gal), 93.5 to 140 L (10 to 15 gal), and less than 93.5 L (10 gal) of propane per hectare, respectively.

[z] Means with in the same column for a cultivar followed by the same letter are not statistically different according to Duncan's multiple range test ($P \leq 0.05$) .

Table 7. Effect of defoliation treatments on open-end spinning yarn properties of percentage elongation, white specks, and neps, thicks and thins per thousand meters

Cultivar	Treatment [y]	Open-end spinning				
		Elongation (%)	White specks (m^{-2})	Neps (km^{-1})	Thicks (km^{-1})	Thins (km^{-1})
Acala 1517-99						
	Chemical	6.6 a [z]	97 a	313 a	133 bc	35 a
	Green	6.6 a	50 a	305 a	174 a	47 a
	Low	6.5 a	66 a	401 a	163 ab	48 a
	Medium	6.6 a	74 a	308 a	142 bc	40 a
	High	6.7 a	66 a	312 a	130 c	35 a
	P	0.0698	0.6632	0.8023	0.0321	0.0632
Delta Pine 565						
	Chemical	6.9 a	58 a	225 a	138 a	55 a
	Green	6.9 a	39 ab	145 a	125 a	56 a
	Low	6.9 a	0 c	111 a	102 b	48 a
	Medium	6.9 a	27 b	107 a	101 b	45 a
	High	6.9 a	39 ab	129 a	103 b	50 a
	P	0.9933	0.0089	0.5204	0.0029	0.2848

[y] Chemical treatment was (2.34 L/ha Finish and 0.51 L/ha Gin Star) and the green treatment was the untreated control. Low, medium, and high were the experimental thermal treatments that used more than 140 L (15 gal), 93.5 to 140 L (10 to 15 gal), and less than 93.5 L (10 gal) of propane per hectare, respectively.

[z] Means with in the same column for a cultivar followed by the same letter are not statistically different according to Duncan's multiple range test ($P \leq 0.05$) .

Table 8. Effect of defoliation treatments on coefficients of variation in irregularity, card sliver and finish draw, major and minor faults, and long thicks and thins

Cultivar	Treatment [y]	Open-end spinning						
		Irregularity C.V. (%)	Card sliver C.V. (%)	Finish draw C.V. (%)	Major faults	Minor faults	Long thicks	Long thins
Acala 1517-99								
	Chemical	15.3 b [z]	3.2 a	3.8 a	0.5 a	58 b	0.0 a	4 a
	Green	15.9 a	3.4 a	4.4 a	0.3 a	161 a	0.0 a	21 a
	Low	15.9 a	3.5 a	4.2 a	0.3 a	117 ab	2.7 a	32 a
	Medium	15.6 ab	3.1 a	4.2 a	0.6 a	104 ab	0.7 a	13 a
	High	15.5 ab	3.0 a	4.1 a	0.0 a	67 b	5.0 a	18 a
	P	0.0347	0.8024	0.3499	0.9054	0.0293	0.0615	0.1923
Delta Pine 565								
	Chemical	15.9 a	3.0 a	3.8 a	0.0 a	77 a	0.5 a	14 a
	Green	15.8 a	3.0 a	4.0 a	0.0 a	59 a	0.0 a	29 a
	Low	15.5 ab	2.8 a	3.6 a	0.0 a	43 a	0.7 a	17 a
	Medium	15.4 b	2.8 a	3.8 a	0.1 a	60 a	0.1 a	29 a
	High	15.5 ab	3.5 a	3.7 a	1.3 a	59 a	0.0 a	7 a
	P	0.0350	0.5623	0.5696	0.1028	0.8952	0.5034	0.6783

[y] Chemical treatment was (2.34 L/ha Finish and 0.51 L/ha Gin Star) and the green treatment was the untreated control. Low, medium, and high were the experimental thermal treatments that used more than 140 L (15 gal), 93.5 to 140 L (10 to 15 gal), and less than 93.5 L (10 gal) of propane per hectare, respectively.

[z] Means with in the same column for a cultivar followed by the same letter are not statistically different according to Duncan's multiple range test ($P \leq 0.05$) .

Table 9. Effect defoliation treatments on lint turnout, fiber value, gross return, and difference in net return for each cultivar

Cultivar	Treatment [v]	Lint turnout (%)	Fiber value ($ kg^{-1})	Gross return ($ ha^{-1}) [w]	Cost of chemical or fuel ($ ha^{-1}) [w]	Difference in net return ($ ha^{-1}) [w, x]
Acala 1517-99 (yield = 1.94 bale ac)						
	Chemical	31.8 a [y]	1.10 b	1150	102	-- [z]
	Green	37.7 a	1.07 b	1118	0	70
	Low	33.5 a	1.08 b	1134	21	65
	Medium	34.0 a	1.17 a	1222	37	137
	High	33.5 a	1.17 a	1224	54	122
	P	0.1666	<0.0001	NA	NA	NA
Delta Pine 565 (yield = 2.53 bale ac)						
	Chemical	35.8 a	1.21 a	1646	102	-- [z]
	Green	35.8 a	1.19 a	1619	0	75
	Low	36.7 a	1.18 a	1607	24	39
	Medium	36.1 a	1.20 a	1634	37	52
	High	34.7 a	1.22 a	1659	56	58
	P	0.7739	0.2420	NA	NA	NA

[v] Chemical treatment was (2.34 L/ha Finish and 0.51 L/ha Gin Star) and the green treatment was the untreated control. Low, medium, and high were the experimental thermal treatments that used more than 140 L (15 gal), 93.5 to 140 L (10 to 15 gal), and less than 93.5 L (10 gal) of propane per hectare, respectively.

[w] Statistics are not available because average yields were used for calculating area-based economic values. The numbers presented are individual estimates and not the mean of several observed data points.

[x] The difference in net return is provided only as a means to estimate what would be a reasonable labor and machinery cost for applying thermal treatments. In calculating the standard chemical treatment, both application and materials cost were included. Costs for thermal treatments only included materials (propane fuel). Application cost for thermal treatments was not available, but would need to be less than the difference in net return for thermal defoliation to be economic.

[y] Means with in the same column for a soil type and cultivar followed by the same letter are not statistically different according to Duncan's multiple range test ($P \leq 0.05$) .

[z] Chemical standard is basis for comparison.

For organic producers, chemical defoliation is not an option. Higher fiber value resulting from higher fiber quality could offset part of the cost of applying thermal treatments, but additional years of data need to be gathered and price premiums for organic fiber need to be considered to make a sound economic analysis.

CONCLUSIONS

Thermal treatment was able to prepare cotton sooner than the chemical control for harvest without damaging fiber or seed.

On the Brazito fine sandy loam soil, where plant respiration had ceased, thermal treatments resulted in less defoliation than chemical treatment. Applying heat to dead plants appeared to "stick" their leaves. Compared with standard chemical defoliation, thermal treatment resulted in more rapid and more complete leaf kill. Leaves on plants subjected to thermal treatment were brittle and crumbly, while those on chemically defoliated plants tended to be tough and leathery.

Cotton gin cleaning equipment removed foreign matter effectively. Lint from thermally-treated cotton was cleaner than lint from chemically defoliated plots. Thermal treatments did not result in damage to fiber or yarn properties. Medium and high levels of thermal treatment, over 93 L of propane per hectare (10 gal/a), resulted in classing office grades and bale values equal to or higher than grades and values achieved by chemical defoliation.

Due to improved fiber quality and value, it was estimated that producers could spend up to $137/ha

($55/acre) to thermally defoliate Acala 1517-99 and up to $58/ha ($23/acre) to thermally defoliate Deltapine 565. If labor and machine costs associated with heat treatment prove to be less than this amount, thermal defoliation could be a profitable practice for cotton producers.

DISCLAIMER

Mention of trade names or commercial products in this article is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U. S. Department of Agriculture.

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REFERENCES

American Society for Testing and Materials (ASTM). 1996a. Standard test method for non-lint content of cotton (D2812-95). p. 722-727. *In* Annual Book of ASTM Standards. Vol. 07.01. ASTM, West Conshohocken, PA.

American Society for Testing and Materials (ASTM). 1996b. Standard test method for breaking strength and elongation of cotton fibers (flat bundle method) (D1445-95). p. 406-413. *In* Annual Book of ASTM Standards. Vol. 07.01. ASTM, West Conshohocken, PA.

American Society for Testing and Materials (ASTM). 1996c. Standard test method for length and length uniformity of cotton fibers by fibrograph measurement (D1447-89). p. 414-418. *In* Annual Book of ASTM Standards. Vol. 07.01. ASTM, West Conshohocken, PA.

American Society for Testing and Materials (ASTM). 1996d. Standard test method for fiber length and length distribution of cotton fibers (D5332-92). p. 715-718. *In* Annual Book of ASTM Standards. Vol. 07.02. ASTM, West Conshohocken, PA.

Association of Official Seed Analysts (AOSA). 2003. Rules for Testing Seeds. p.113. *In* L. Capshaw (ed.) Rules for testing seeds. AOSA, Las Cruces, NM.

Batchelder, D.G., J.G. Porterfield, and G. McLaughlin. 1971. Thermal defoliation of cotton. p. 36-37. *In* Proc. Beltwide Cotton Conf., Atlanta, GA. 12-13 Jan. 1971 . Natl. Cotton Council. Am., Memphis, TN.

Falconer, L. 2002. Cotton loan valuation decision aid. Cotton Incorporated, Cary, NC. Available online at http:/www.cottoninc.com/Agriculture/homepage.cfm?PAGE=3775. (verified 9 Sept. 2004).

Funk, P.A., B.E. Lewis, and S.E. Hughs. 2001. Preliminary thermal defoliaion trials. p. 323. *In* Proc. Beltwide Cotton Conf., Anaheim, CA. 9-13 Jan. 2001 Natl. Cotton Council. Am., Memphis, TN.

Funk, P.A., C.B. Armijo, B.E. Lewis, R.L. Steiner, and D.D. McAlister, III. 2002. Thermal defoliation. p. 6. *In* Proc. Beltwide Cotton Conf., Atlanta, GA. 8-12 Jan. 2002. Natl. Cotton Council Am., Memphis, TN.

Funk, P.A., C.B. Armijo D.D. McAlister, III, A.D. Brashears, J.S. Bancroft, B.A. Roberts, and B.E. Lewis. 2003. Thermal defoliation. p. 2549-2553. *In* Proc. Beltwide Cotton Conf., Nashville, TN. 6-10 Jan. 2003. Natl. Cotton Council Am., Memphis, TN.

Kent, J.D. and J.G. Porterfield. 1967. Thermal defoliation of cotton. Trans. ASAE 10(1):24-27.

Merrigan, K.A. 2000. The national organic program: regulatory text. USDA-Agricultural Marketing Service. Available online at http://www.ams.usda.gov/nop/NOP/standards/FullRegTextOnly.html verified 28 Apr. 2004).

Nisbet, C. and C.S. Nisbet, Jr. 1954. Apparatus for subjecting cotton plants and the like to hot gasses. U.S. Patent 2,682,728. Date issued: 6 July 1954.

Porterfield, J.G. and D.G. Batchelder. 1969. Thermal defoliator. U.S. Patent 3,442,262. Date issued: 6 May 1969.

Porterfield, J.G., D.G. Batchelder, W.E. Taylor and G. McLaughlin. 1970. 1969 thermal defoliation. Seventh Annual Symposium on Thermal Agriculture, Dallas, TX. 22-23 Jan. 1970. National LP Gas Association. Published as Oklahoma Agric. Exp. Sta. Journal Manuscript No. 1948.

Wheeler, J.R. and R.F. Ford. 1974. Defoliation with heat. p. 57-61. *In* Proc. Beltwide Cotton Conf., Dallas, TX. 7-9 Jan. 1974. Natl. Cotton Council Am., Memphis, TN.

Shepherd, J.V. 1972. Standard procedures for foreign matter and moisture analytical tests used in cotton ginning research. Stock No. 0100-1509. U.S. Gov. Print. Office, Washington, D.C.

USDA - Farm Service Agency (FSA). 2002. Price support loan rates. Available online at http://www.fsa.usda.gov/dafp/psd/loanrate.htm (verified 28 Apr. 2004).