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Technical Note

Chemical-Free Cotton Defoliation by; Mechanical, Flame and Laser Girdling

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Academic Editor: Leslie A. Weston
Received: 6 September 2016; Accepted: 19 January 2017; Published: 25 January 2017

Abstract: A novel new way to achieve chemical-free defoliation of cotton is discussed. The research found that by severing the phloem tissue on the main stalk, via a girdling operation, the operation stimulated the cotton plant to alter its growth into an early senescence pathway that resulted in the plant shedding its leaves and opening up all its bolls, leaving the plant in the perfect state for machine harvesting. Even with follow-up rains, zero regrowth occurred in the treated plants, unlike the untreated control plots where significant regrowth did occur. This report compares the results of greenhouse and field trials where the girdling operation was performed by hand, flame, mechanical and via a CO_2 laser to achieve phloem tissue severance. Design parameters for a prototype laser girdling system are also provided. Results suggest that for deficit irrigated cotton, girdling can provide an alternative means to defoliate cotton.

Keywords: cotton defoliation; cotton desiccation; laser treatment; girdling

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1. Introduction

Modern cotton production utilizes aggressive measures to terminate the life of the plants so as to enable early harvest and thereby preserve the quality of the cotton fiber. In the quest to harvest early, growers must contend with green leaves that stain the cotton fibers if left on the plants. Thus, standard practice for harvest preparation is to spray the plants with a combination of chemicals to achieve leaf drop prior to the harvest operation. As the growers typically seek to enter the field as early as possible, to avoid leaving valuable lint in the field, harvest preparation has the additional goal of opening up any unopened economically viable cotton bolls. In the organic markets, there are currently no chemical options for achieving these objectives. The only currently known organic option is to utilize a propane heat treatment. However, this treatment method has proven to be cost prohibitive and is typically not economically viable. Recent work by the authors examined if plant sugars could be relocated at harvest time through a girdling operation, as is done in other crops such as grapes and stone fruit trees [1–3]. This initial research, by the authors, suggests that it might be possible to defoliate cotton plants by girdling the plant after the cut-out stage of growth. It appeared that the plant growth progression was altered to follow an early senescence apoptosis programmed cell death pathway that led directly to boll opening and leaf drop over a period of 4–7 weeks. This observation was very different than reported in literature [4] who reported on effects of girdling on early stage growth in cotton. Their findings found a reduction in shedding of squares and bolls with no significant differences in yield. The perspective that they did not observe defoliation is supported by their reporting being limited to potential improvement of water use efficiency. No observation of early senescence was reported. The only other significant studies that were found by the authors, was for girdling caused by misuse of hooded sprayers which was reported as leading to a quick death in young cotton seedling [5]. Literature on girdling of trees provides a mixed record as well with some reports of tree kills taking from 5–22 years or more after girdling [6]. Other reports discussed observing early senescence in some trees along with a low efficacy for girdling to thin trees in forests [7]. This unique observation by the authors of defoliation and boll-opening occurring in cotton from girdling led to this study to explore the potential for chemical-free defoliation by girdling of the main cotton stalk.

This research was undertaken to explore this new found physiological trait with the hope to develop a means to girdle the plants at a commercial scale. The current focus of this research is to evaluate efficacy of this new treatment as well as on the potential utilization of CO_2 lasers to achieve the girdling cut of the main stalk and thereby provide a means to achieve commercial scale-girdling operation economically.

1.1. Laser Background

Recent research reported in the literature explored the potential of CO_2 lasers for use in burning down weeds. One approach utilized a horizontal laser and cut off the weeds close to the ground [8,9]. Later research along these same lines found that enhanced efficiency could be achieved by targeting the apical meristem of the weeds at the cotyledon stage, with optimal performance at or below the two-leaf stage at a threshold energy level of 3–5 J mm^{-2} [10–13]. Of note about this research is that they limited their research to young seedlings, and reported poor efficacy of treatment on larger plants above the three- to four-leaf stage. Noting that the plants of interest to this research are full-grown plants ready for harvest, coupled with the known physiological trait that a termination of the meristem only causes additional branching in mature plants, this research is likely only relevant to establish guidance on minimal power requirements. One would also expect from reported use of CO_2 lasers in the wood industry that a suitable system would draw significantly more power as the plants get older and the main stalks get thicker bark coatings over the nutrient-carrying phloem tissues. Moreover, by extension, these more mature plants should require more energy to penetrate deeper into the bark and woody structures of the plants rather than the delicate meristems of young seedlings, as reported in the previously discussed literature. Beyond this work, the authors were unable to find references applicable for guidance on laser girdling.

1.2. Research Objectives

The main objective of this research, and reported on herein, is to assess the potential utilization of girdling to achieve defoliation and to develop the necessary engineering parameters associated with the operational characteristics that a working CO_2 laser would have to provide in order to create a girdling cut on the main stalk of a cotton plant at harvest time. The specific objectives are to :

- develop the efficacy of girdling to achieve defoliation;
- assess various options to mechanize girdling operation to help scale the operation to commercial practices;
- determine machine specifications for a laser-powered cotton stem girdling implement;
- determine power and dwell time requirements for a CO_2 laser to achieve main stem cutting at a depth sufficient to at least penetrate and sever the underlying phloem tissue;
- ascertain the upper-end power level limit, beyond which results in lodging of the plant and loss of that plant's contribution to the yield;
- collect basic information regarding bark depth versus height and stalk diameter (for future use to help control the power to the plant size);
- identify if power control modulation is required based on plant height of main stalk diameter.

2. Materials and Methods

2.1. Test Methods

To explore the effects of girdling on cotton, several techniques were utilized to girdle the main stem on the cotton plant through to the white wood, thereby essentially removing all the bark and phloem tissue in the girdled ring. To evaluate the methods, three trials were conducted;

- Greenhouse study utilizing 45 plants that were grown in two blocks, where blocking was the pot size. In block one, 24 plants were grown in standard 4 L pots (small), with an additional 21 plants that were grown in large 11 L pots. Each block was further sub-divided into three groups (control, hand knife girdled, laser girdle). Plants were grown utilizing standard greenhouse practices until there were 20% or more naturally opened bolls before the plants were treated. The plants were drip irrigated two to three times per day utilizing a standard half-strength Hoagland solution. The soil medium was a standard peat greenhouse mixture that had an additional slow release fertilizer amendment that was added to the mixture.
- Outdoor-grown study utilizing potted plants to re-evaluate CO_2 laser treatment utilizing a more powerful laser configuration. Plants were configured in a similar manner to greenhouse study, again utilizing the large 11 L pots.
- Field trial where each treatment was a timing and a girdling method, so treatments were (T1_Hand_knife_Girdle, T1_Mechanical_Girdle, T1_Control_untreated, T2_Hand_knife_Girdle, T2_Mechanical_Girdle, T2_Control_untreated, T3_Hand_knife_Girdle, T3_Mechanical_Girdle, T3_Control_untreated, T4_Hand_knife_Girdle, T4_Mechanical_Girdle, T4_Control_untreated, T4_Control_Chemical_Defoliation, T2_Flame_Girdle). In each of these, the "Tx" refers to the week in which the girdling operation was performed on the main stalk. T1 refers to the earliest treatment and T4 the last treatment that coincided with the chemical application of the defoliant applied to only the T4_Control_Chemical_Defoliation, which was effectively the rest of the field as separated by a 20-row buffer zone. After the chemical application, the crop was monitored for defoliation progress, per standard commercial practices and when it was observed to be ready, it was harvested. Due to late season rains, during the year of the study, this occurred 21 days after the application. Each treatment plot was 3 m in length that was furrow irrigated row crop cotton plants grown under commercial practices in West Texas, United States, where due to limited water availability, the plants are grown under deficit irrigation practices. On either side of each treatment plot were two control plots. Plant spacing was such that approximately 30 plants occupied every 3 m of row. The plants were planted in the center of the row, single-spaced and the bed-rows were placed at one meter′s spacing between each row. Of importance is that, due to the deficit irrigation limitation, the plants were of normal size for the region, but were substantially smaller than is typical for plants grown in other regions of the United States where water is not limited. Also noteworthy is that 40%–50% of all United States cotton is grown in this region under these conditions and practices. The main treatments evaluated in this trial were senescence timing and girdling method (hand knife, mechanical flap-brush). For additional information, flame heating of main stalk was added on an additional plot during week 2 treatments. Two control methods were evaluated; untreated plants grown on either side of the treated row and a standard practice chemical defoliation treatment. Timing treatments were configured to allow for from four to seven weeks to pass before the plants were harvested, enabling evaluation of the effect of timing on the senescence progression on standard plant variables such as lint yield, number of bolls and lint weight per boll. The soil type for the trail was a sandy clay loam typical to the region. For the field test, all the plants were harvested on the same day with the only variants being the method of defoliation and when the defoliation treatment was performed. Notation utilized was that Hand-1 refers to the plants that were treated first, and hence had the most time to progress through the senescence process. Mech-1 was performed at the same time utilizing the mechanical rotary tool with a flap-brush installed in it. Hand-2 and Mech-2 followed one week later; Hand-3 was performed two weeks later than Hand-1. The flame treatment was an initial feasibility treatment and was only performed once during week 2 of the treatments.

2.2. Hand, Flame and Mechanical Girdling Methods

To achieve girdling of the main stalk on the cotton plant, several techniques were explored. Figure 1 shows the hand method which utilized a knife to cut the bark down to the white wood, at the base of main stalk, to sever and terminate the sap flow in the phloem tissue. The width of the cut was approximately 6 mm.

Figure 1. Cotton main stem hand knife girdling utilized to promote chemical-free defoliation.

The flame girdling treatment was performed with a hand-held burner, like the one shown in Figure 2.

Figure 2. Flame girdling of field-grown cotton plants.

The mechanical girdling treatment was performed with a hand-held rotary tool that held a flap-brush. Results of the action of the mechanical treatment on the main cotton stalk are shown in Figure 3.

Figure 3. Results of mechanical girdling of field-grown cotton plants utilizing a hand-held motorized flap-brush.

2.3. Laser Girdling

One of the study's main sub-objectives, as stated in an earlier section, consisted of the development of a micro-controller-based, computer-numerical-controlled (CNC) CO_2 laser treatment station that could be precisely controlled for power levels (duty cycle) and travel speed. By putting a laser beam deflection mirror on a moving CNC carriage, the system was able to simulate forward travel past a stationary cotton plant. To allow the micro-controller to precisely control the velocity of the laser beam as it moves across the plant, the micro-controller sends control signals to a bridge driver that provides a multi-phase waveform to actuate a 4 Amp stepper motor that turns a 1/2″ two-turn leadscrew that translates both mirrors past the fixture holding the plant (Figure 2). The 4 V Stepper motor was powered by 24 V to increase the low-end torque and high-end speed. Bearings for the CNC are 20 mm linear rail-bushing combinations. Frame for the laser housing and CNC supports was constructed out of 30 mm × 30 mm t-slot extruded aluminum tubing. The steering mirrors, for the 10,000 nm CO_2 laser beam, were a 30 mm dia. Gold-plated front surface mirror. The focusing lens was a ZnSe 25 mm dia. lens with a 100 mm focal point. A picture of the experimental apparatus is detailed in Figures 4 and 5.

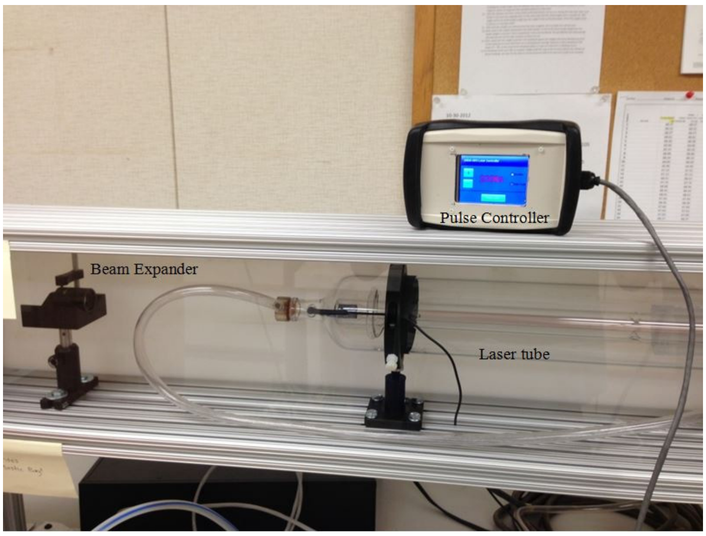

Figure 4. Experimental micro-controller-based computer-numerical-controlled (CNC) CO_2 laser treatment system designed to provide precise control over the laser treatment time and energy density.

Output of the laser system is sent to a moving mirror on a single-axis CNC platform. Figure 5 shows the moving mirror as well as a stationary jig to hold the cotton plants while they are being treated.

Initial testing was conducted using an unfocused 40 W CO_2 laser. Tests indicated it had more than sufficient power for cutting through leaves, but was much too low for the stated purpose of slicing through bark down to below the phloem layer. To improve the power density, focusing lenses were added to the system to achieve a significant increase. Further tests revealed this setup still could not penetrate all the way through the bark. The next improvement was to exchange the 40 W laser for a 100 W laser. Due to both size and cost constraints, this laser was the last one adopted for the testing portion of the study and the specifications as utilized in the study were:

- raw beam output diameter 4 mm;
- raw beam 100% output power density 8.0 W mm^{-2};
- tube length: 1460 mm (mirror to mirror distance);
- triggering voltage 30 kV;
- operating voltage 22 kV;
- current at full power 30 mA;
- diameter of outer cooling tube 80 mm;
- diameter of inner CO_2 gas tube 15 mm;
- cooling method for continuous use water;
- cooling method for intermittent laboratory use 2–4 s bursts of air @ 15.3 L min^{-1}.

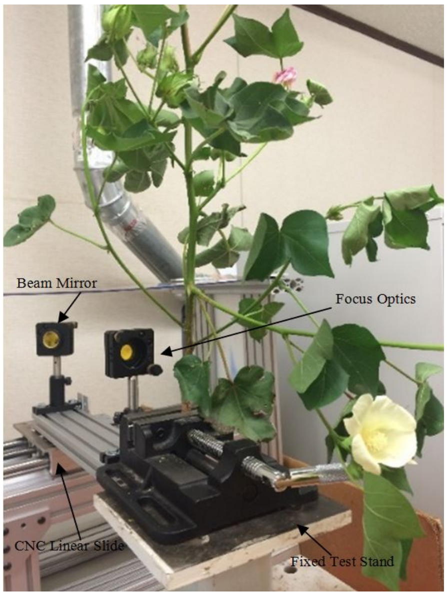

Figure 5. Experimental micro-controller based CNC CO_2 laser treatment system designed to provide precise control over the laser treatment time and energy density.

As the applied power was still insufficient, a study was conducted on the effect that various focal length lenses would have on the effective energy density and hence cutting power. The lenses studied were 50, 100 and 200 mm. The design trade-offs between a lens with a short focal length versus a long focal length, were: the short focal length lens creates a significant increase in power density, it also reduces the distance from the lens to the target and significantly reduces the depth of field where the laser is in focus and at maximum power density. As working near the main stem was difficult, a 1.5× beam expander was adopted to help increase the focal distance offset. In practice, even with the 1.5× beam expander, the 50 mm lens required much too close of a distance to the focusing lens to be practical. On the other end, the 200 mm lens provided a great offset, but did not provide enough power gain to fully penetrate the thick bark of the mature cotton plants. For the remainder of the testing, the configuration described above was utilized with a 100 mm lens. This resulted in a beam power density of 2100 W mm^{-2} which did provide an adequate amount of power. The trade-off to this approach is that the depth-of-field for the operational distance collapses with focusing lenses. A significant improvement would be achieved once 2 kW lasers become more affordable, that do not require focusing optics. Testing revealed 100 mm lens combination with 1.5× beam expander provided a 7.5 mm depth of field with a spot diameter of 0.25 mm. Table 1 provides details on impact of energy density fall-off as one moves away from the in-focus zone. Energy density calculation assumes a linear forward speed of 25 mm s^{-1}, thereby providing an estimated treatment time for the required traversal from one side of the spot to the other (spot diameter).

Table 1. CO_2 laser energy density at varying distances from the 100 mm lens for 100% duty cycle (un-modulated excitation voltage).

Distance from Lens to Front of Cardboard	Diameter of Incision	Area	Energy Ratio	Energy Density
(mm)	(mm)	(mm^2)	(mm^2 mm^{-2})	(J mm^{-2})
101.60	0.82	0.53	0.54	10.84
104.14	0.61	0.29	0.97	19.59
106.68	0.60	0.28	1.00	20.25
109.22	0.79	0.49	0.58	11.68
111.76	1.05	0.87	0.33	6.61
114.30	1.13	1.00	0.28	5.71
127.00	1.59	1.99	0.14	2.88

Given the required use of lenses, a test was conducted to gain insight into how rapidly the power falls off as the target moves away from the ideal focus zone. To provide this test, a spot burning card test was conducted. During the test, a card was placed at steadily increasing distances between spot burns to allow quantification for each offset distance and burn-spot diameter. Spot test parameters were

- Stationary head (CNC movement turned off);
- Laser excitation duty cycle 25%;
- Laser beam excitation burn time 300 ms.

Using data from spot test allowed for creation of a function (Figure 6) relating energy density as a function of distance from the target (assumes burn location is only on far side of focal length).

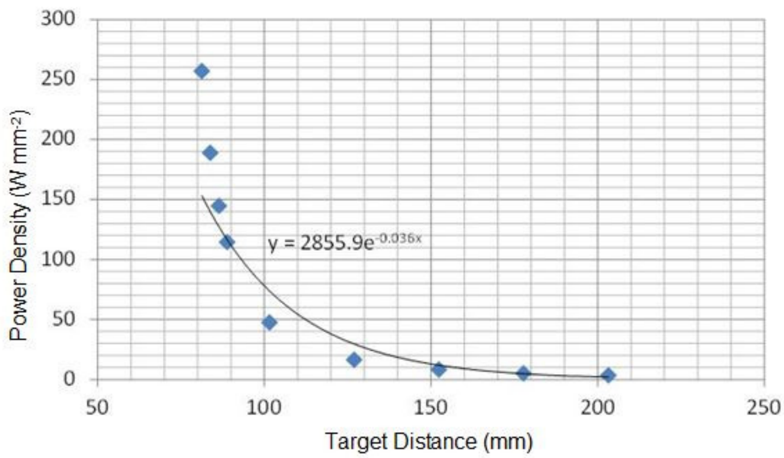

Figure 6. Experimental micro-controller based CNC CO_2 laser treatment system designed to provide precise control over the laser treatment time and energy density.

2.3.1. Laser Laboratory Experimental Design

Field-grown cotton plants were harvested from various locations under commercial practices common to the West Texas area in the continental United States. The test protocol was to measure the height of the stem from both the cotyledon to the apical meristem in the laboratory, as well as in the field from the soil to the apical meristem. Immediately upon harvest, the roots of the plants were covered in wet towels and wrapped in plastic for the ten-minute transport back to the laboratory, whereby they were immediately placed into the test system for measurements and laser treatment. Upon arrival at the laboratory, the roots were removed and the stem was placed into the test holder with the closest point of the stem positioned at the optimal in-focus region (Figure 5). The distance from the lens was approximately 100 mm, which corresponds to the focal length of the selected lens, with the actual focal point established via experimental burn testing. The laser was then fired for one or two passes across the stem, by indexing the CNC laser as the laser was fired using pulse-width modulation control from the micro-controller to achieve the desired power levels and burn durations. Treatments consisted of one to multiple cuts at various duty cycles. For each test subject, the diameter of the stem was measured at each location of the cut, in two directions; a first diameter measurement was taken from the point where the laser beam would hit the stem to the back of the stem, and a second diameter measurement was taken from side to side of the stem. To obtain the stem diameter, these measurements were averaged to obtain a mean diameter which was the reported stem diameter for that plant. After completion of the test laser cut, the bark of the stem was dissected at the location of the laser cut, in such a way that the white wood, xylem tissue, below the bark could be examined for damage assessment. Noting the phloem nutrient transport tissue resides just under the bark and closer to the surface than the white xylem wood, allows for the experiment to quantify the level of damage of the laser cut to ensure penetration of the laser cut into the phloem tissue. The depth of the cut made into the white wood was measured and recorded for later assessment of power damage relationships. The dissected section of the bark was measured to quantify the bark thickness for that plant specimen.

2.3.2. Laser Greenhouse and Field Trial Experimental Design

Utilizing the laser treatment system discussed in the earlier sections, the greenhouse-grown plants were girdled. To achieve a similar result to the hand knife girdled plants where the girdled area was 6 mm in width, the test was set up to perform multiple passes on each of the two sides. The passes on each side were spaced at 2 cm. As the objective is a field-based implement, the passes were limited to two sides that were 180 degrees in opposition. This was deemed the most practical approach that would readily scale to a field-driven implement, even though it was recognized that this method left a small ribbon of bark untreated on either side of the stalk. To ensure repeatable results between plants, the CNC was configured to travel at one treatment speed and the plant was positioned such that the focal length was at the front edge of the stalk, nearest to the laser. Figure 7 shows technicians performing the girdling operation on one of the greenhouse-grown plants.

Figure 7. Girdling with CNC CO_2 laser treatment system on greenhouse-grown cotton plants.

3. Results

3.1. Greenhouse Girdling Trial

The early senescence onset in mature plants was first observed by the authors in a greenhouse study. Figure 8 shows the progression of one of the first study plants over the course of its progression from healthy through apoptosis, via a slow senescence, which was observed with typical lowering of chlorophyll and enhanced anthocyanin response to finally full leaf drop. This progression took place over a four- to seven-week period. Of importance is that during this progression, the plant did not just die and drop all of its leaves. During this progression, all the bolls opened, even those that were initially green and fully closed near the top of the plant when the girdling operation was performed.

Figure 8. Cotton plant stimulation of apoptosis early programmed cell death via stem girdling. Images from left to right show how one specimen stimulated by main stem full girdling, progress from healthy through early senescence to eventual full boll opening and leaf drop.

After the initial observation, a full greenhouse test was conducted on 45 plants that were blocked across two different pot sizes (24 in small pots, 21 in large pots). The results of the study showed that for the plants grown in the small pots, the efficacy of the hand knife girdling was near 100%, with both the untreated control plants and the laser girdled plants showing little if any defoliation, Figure 9.

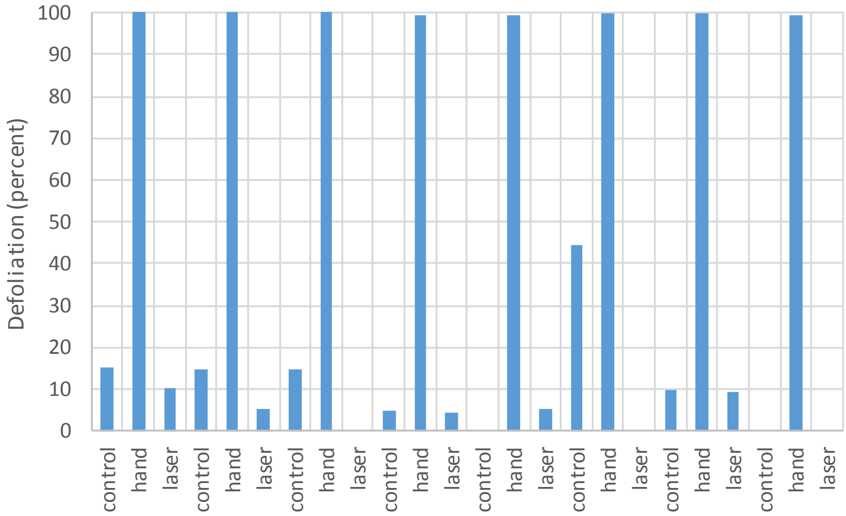

Figure 9. Defoliation efficacy for greenhouse-grown plants utilizing small 4 L pots for replicated comparison of (control, hand-girdled, laser-girdled).

However, the large plants in the large pots were much different with some of the plants exhibiting healing growths at the girdling site. As seen in Figure 10, only a small fraction of the hand knife girdled plants, grown in the large pots, exhibited the desired defoliation response. Again, none of the control or laser girdled plants exhibited the defoliation response.

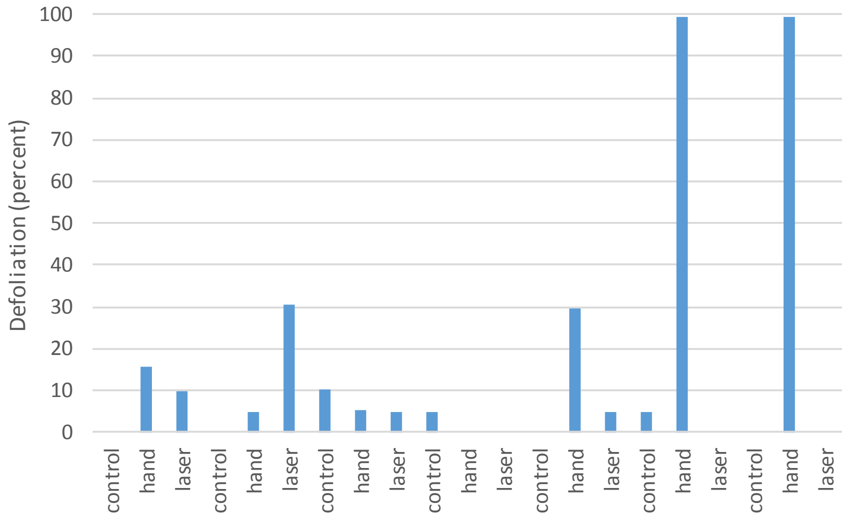

Figure 10. Defoliation efficacy for greenhouse-grown plants utilizing large 11 L pots for replicated comparison of (control, hand-girdled, laser-girdled).

In looking at the response between total number of bolls, for the plants grown in the small pots, no significant differences were observed between any of the treatments, Figure 11.

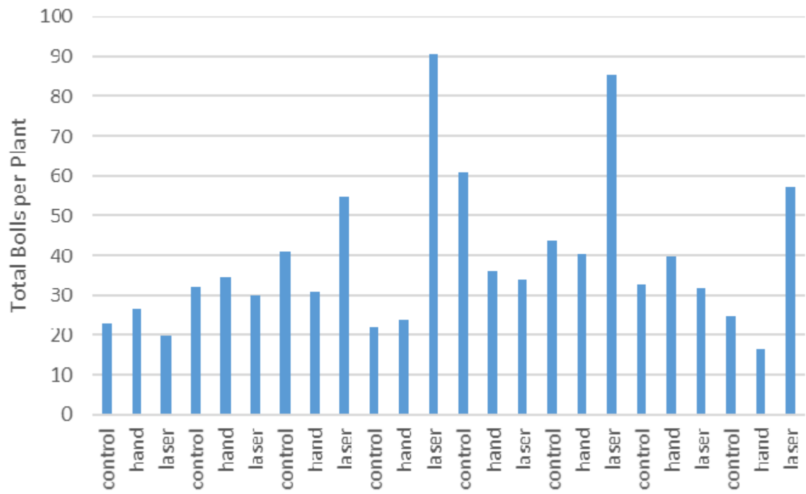

Figure 11. Boll counts for greenhouse-grown plants utilizing small 4 L pots.

Similarly, for the plants grown with the large pots, again no significant differences were detected between treatments, Figure 12.

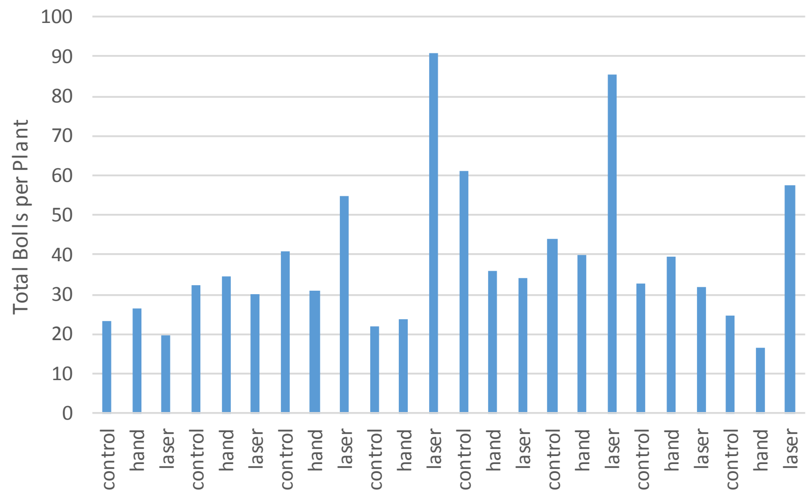

Figure 12. Boll counts for greenhouse-grown plants utilizing large 11 L pots.

Noting the near 100% efficacy for the plants grown in the small pots versus only 28% efficacy for the plants grown in the large pots, a hypothesis was formulated that the size of the root mass, could be a key factor in determining if the defoliation response would occur. Noting that greenhouse plants are significantly different than field-grown plants, a field trial was conducted to ascertain which of these two defoliation responses would transfer to the field-grown plants.

3.2. Field Girdling Trial

The field trial response showed a near perfect defoliation response, as long as the treatment time was sufficiently long, so as to allow for the plant enough time to undergo the slow senescence progression. The plants treated with the hand knife girdling, showed near 100% defoliation response when they had six to seven weeks to progress. The plants that only had five weeks or less did not show a progressively weaker response. Figure 13 compares the control untreated plants and the plants that were treated in week one and hence had the longest time to undergo the senescence response. The plants that were treated in week two exhibited a similar response.

Figure 13. Cotton plants in left frame were naturally defoliated by triggering early senescence by main stem girdling. Cotton plants in the right frame were the control plants that were untreated (pictures taken on same day and were in neighboring rows).

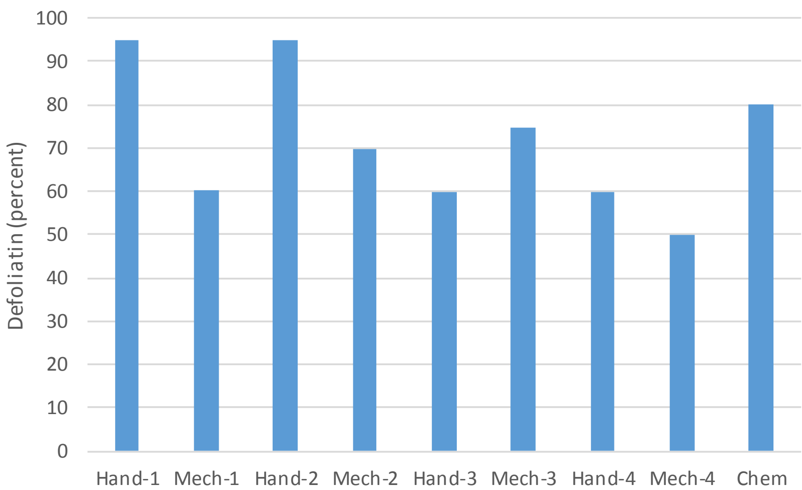

Figure 14. Defoliation estimation for field cotton grown under commercial practices common to deficit irrigated cotton in West Texas, United States. Note: the numeral following each treatment refers to which week they were treated by girdling along with the girdling method (hand knife, mechanical flap brush, chemical defoliation (control), flame girdling). Therefore, Hand-1 was treated the first week of October, Hand-2 during the second week and so on. Total growing time for all plants were identical. The only difference between type of treatment was duration from treatment to harvest. Hence, the time for Hand-1 plants from treatment until harvest was seven weeks. Hand-2 plants were treated a week later, so had six weeks from treatment until harvest.

The plants treated in week three and four did show some signs of chlorophyll reduction and anthocyanin increase; however, as the season was moving along, the control plants were also starting to show these signs as well, so the observation was only qualitative with no true definitive measure and in week four, the treated plants were indistinguishable from the control plants. A summary graph of the progression as a function of treatment timing is detailed in Figure 14. Of note is that the mechanical treatment in the first week lodged nearly 80% of the plants. After that, the plants were handled much less aggressively, which subsequently resulted in much lower lodging rates, but also less efficacy in defoliation. The untreated control plants exhibited less than 10% defoliation, due to natural leaf dying as the days got shorter and the nights cooler.

The effect of treatment on boll weights did not prove conclusive, as shown in Figure 15.

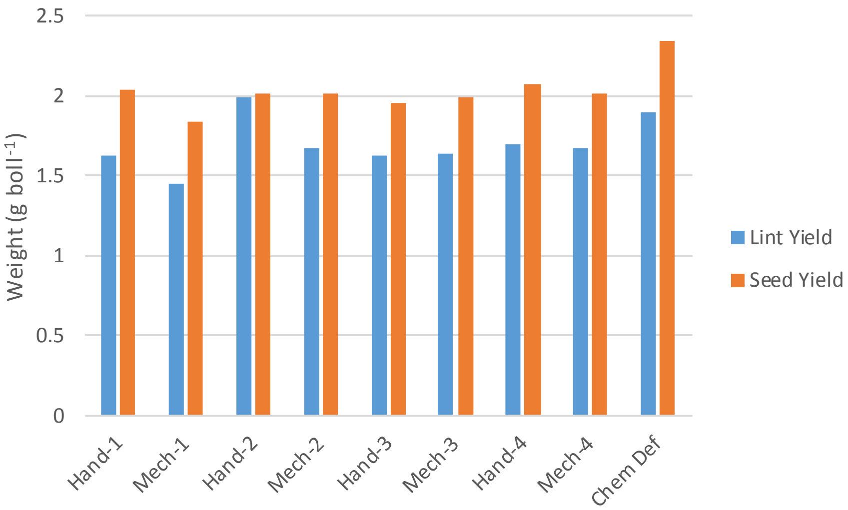

Figure 15. Yield estimation, by lint weight per boll, for field cotton grown under commercial practices common to deficit irrigated cotton in West Texas, United States. Note: the numeral following each treatment refers to which week they were treated by girdling along with girdling method (hand knife, mechanical flap brush, chemical defoliation (control), flame girdling).

However, when examined on a yield basis for total lint weight per plant, the plants treated in weeks 1 and 2 were significantly depressed with respect to the treatments that occurred at later dates. These findings suggest that timing utilizing this technique could be a problem and might lead to slightly lower yields than if one waits and utilizes a conventional defoliation practice. This can be seen in Figures 16 and 17.

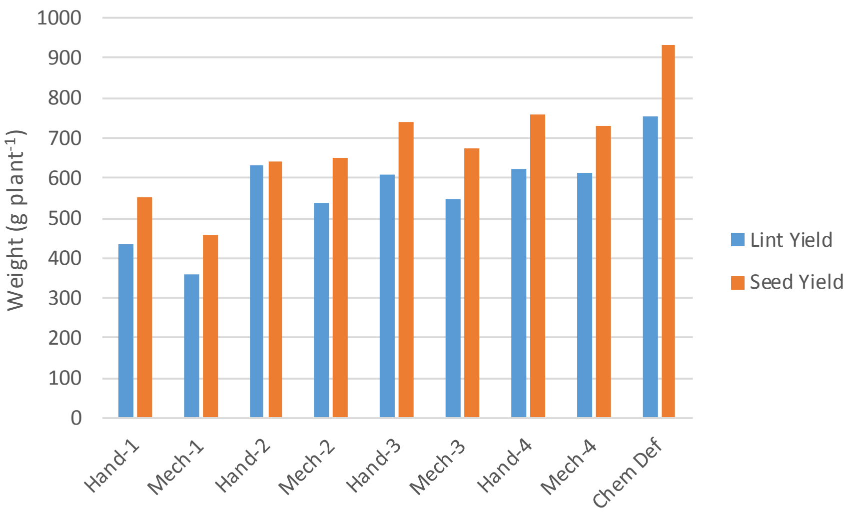

Figure 16. Yield estimation, total lint weight, for field cotton grown under commercial practices common to deficit irrigated cotton in West Texas, United States. Note: the numeral following each treatment refers to which week they were treated by girdling along with girdling method (hand knife, mechanical flap brush, chemical defoliation (control), flame girdling).

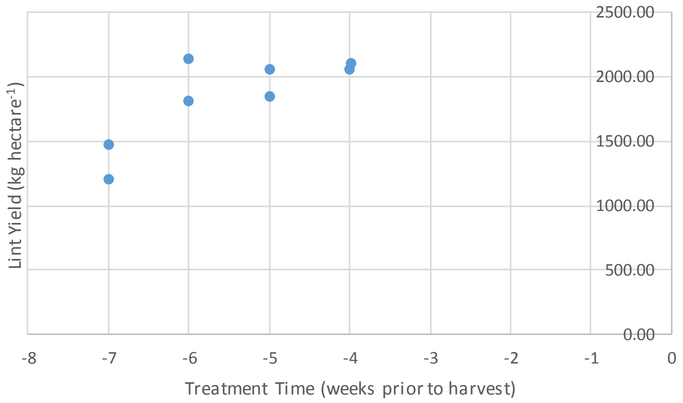

Figure 17. Effect of treatment timing on lint yield, for field cotton grown under commercial practices common to deficit irrigated cotton in West Texas, United States.

3.3. Laser System Laboratory Characterization

The CNC laser system discussed in the previous section was found to provide a reliable means to estimate power requirements to slice through the phloem layer, in a girdling operation, or to completely sever the main plant stem. In treating the plants, it became immediately obvious that in many of the more mature plants, the leaves on feeder branches sometimes occluded the main stem and it took extra passes to penetrate this external blocking foliage. Thus, in practice, these lower hanging branches on the cotton plant will likely have to be lifted out of the way as the tool moves past the cotton plants during a girdling operation.

3.3.1. Cotton Bark Characterization

It was hypothesized that a large plant will require a significantly greater amount of power than a smaller plant, due to the difference in bark thickness between the two plants. In anticipation that this might lead to the need to develop a sensor by which to control laser power based upon bark thickness, this section develops prediction equations, from specimen tests that relate phenotypic traits of plant height and stem diameter to the bark thickness.

The objective of this section is to develop relations which could be used to prototype a bark thickness sensor and hence provide the machine with an estimate of the power requirements that a particular plant would require. Figure 18 details the correlation analysis between the cotton plant's main stalk and the bark thickness. Figure 19 shows a similar analysis between diameter and plant height. Of the two approaches, the diameter measurement provides a much better predictor of bark thickness and is the recommended approach as a basis to predict bark thickness.

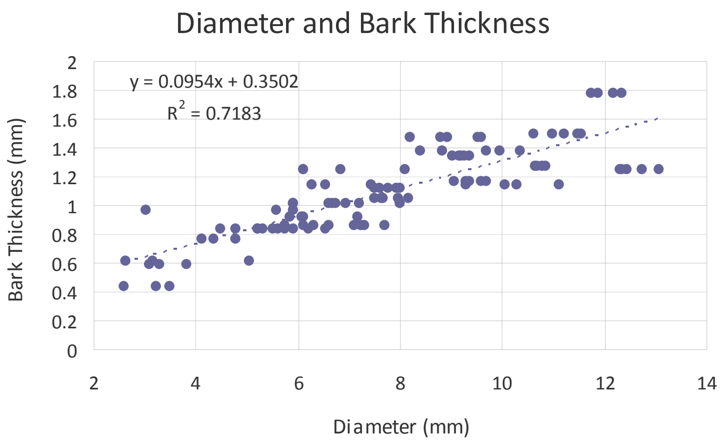

Figure 18. Correlation analysis between the diameter of the cotton plant's main stalk to the bark thickness.

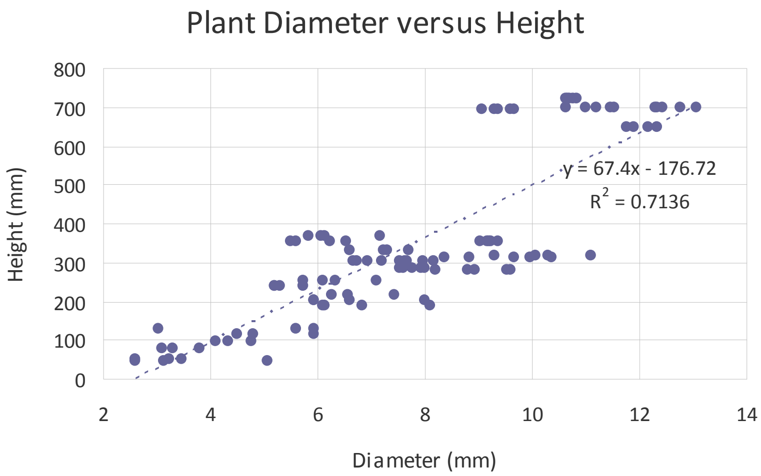

Figure 19. Correlation analysis between the diameter of the cotton plant's height to the bark thickness.

3.3.2. Cotton Bark Penetration Power Requirements

The objective of this section is to determine the safe power levels that will result in a complete cutting of the bark to below the phloem layer, yet not so deep as to damage the structural integrity of the plant, to avoid lodging. To gain insights into what these power levels are, power ramp tests were conducted on freshly harvested young and mature field-grown cotton plants, as well as on outdoor- grown, well-irrigated, mature, container-grown cotton plants. After each test, the plants were destructively harvested and dissected to reveal the penetration depth (Figure 20). Figure 21 details the results from a regression study relating depth of cut to the laser power.

Figure 20. Figures details the results shown from laser power tests that were performed on freshly harvested field-grown cotton plants to determine cutting depth versus laser-power. The figure on left shows the stalk as it was immediately after laser cutting. The figure on right is after removal of the bark to reveal the depth of the laser cut. To ensure complete phloem termination, the white wood should show a laser scar all the way around the perimeter.

To ascertain if a priori knowledge of either bark thickness or stem diameter would help to assess power requirements for optimal girdling cuts, a subset of the data was selected where the laser had just penetrated past the phloem and bark layer by no more than 0.5 mm. A regression analysis on this subset was performed comparing laser power to bark thickness as well as to stem diameter. In both cases, the correlations were exceedingly poor with coefficient of determinations less than $r^2 = 0.05$. Hence, the best guidance for the power requirements for laser girdling treatment of cotton plants in the range from 250 to 725 mm tall is to use 15 J mm^{-2} laser power. For this range of plant sizes typical to West Texas deficit irrigation cotton, the data suggests that a sensor would not provide any improvement over a single fixed output power.

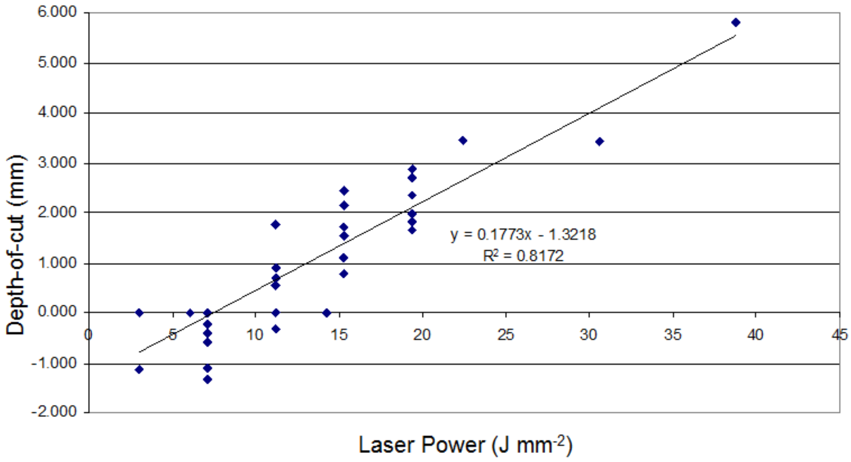

Figure 21. Figure details the regression analysis for the laser power tests that were performed on freshly harvested field-grown cotton plants to determine cutting depth versus laser-power. Results are from plants ranging in height from 250 mm to 725 mm. A zero depth corresponds to the depth where the laser just penetrated through the bark and the phloem tissue. The negative depth indicates insufficient power.

To assess the lodging risk, a subset of the dataset was identified that comprised only those that had lodged when treated with the laser. From this set it was found that, on average, the depth of cut was sufficient to penetrate at least halfway through the stem, with a standard deviation of 0.28. One aspect that should be appreciated with this statistic is that these freshly harvested plants were only subjected to gravity while under treatment and mounted in the fixture. Therefore, they were not subjected to post-treatment wind loading, as field-grown plants would be. Thus, while it appears that the depth of cut could approach 50% penetration of the stem diameter, it is expected that this value is likely a lot lower for field plants. A further assessment of this issue will be left to future research efforts.

4. Conclusions

Chemical-free defoliation of cotton by main stalk girdling was shown to have the potential to be an environmentally friendly method to prepare cotton for harvest. In the small potted plants grown in the greenhouse, the defoliation response was near 100% efficacy. Similarly, for the field-grown plants, it appears that if enough time was provided, girdling the main stalk could provide nearly 100% defoliation response. Thus, the use of girdling does show promise as an alternative method to achieve defoliation. A key constraint with this method is going to be how to judge timing of the treatment, given the long dwell time required to achieve results. There is also the risk with this technique for obtaining lower yields. Given these issues with the technique, practical use in the United States may be limited to niche markets such as organic cotton, or unless regulatory environment presents other constraints that limit the chemicals that can be applied. In other regions of the world, it may provide another welcomed option depending upon the specifics of that region. A key to making this technique practical is to develop a girdling method that can be performed at normal tractor implement speeds and costs, or perhaps with the use of an abundant and low-cost labor force. Towards the potential for achieving the girdling operation on tractor-driven implements, the use of a CO_2 laser to impart the girdling cut was explored. While the efficacy of the trial tested in this research effort was minimal, we note that the girdling was limited in circumference and therefore left a small ribbon of live tissue on either side of the stalk. Further work needs to be done to reassess the efficacy with the CO_2 laser if a full perimeter cut is made. If so, then an engineering solution could be designed to enable the use of a laser girdler which would provide some very interesting benefits from an energy perspective in comparison to previous work where they heated the entire canopy.

The results of the CO_2 laser testing indicated that a 100 W laser traveling 31 mm s^{-1} could impart enough energy to cut through the bark and phloem tissue, thereby effectively girdling the main stem. This speed, however, is too slow to be practical on a commercial basis. Extrapolating from these results to a reasonable speed suggests an increase of 50–100× in power requirements, so a 5–10 kW laser is suggested, if using focusing optics. It is likely impractical to consider a laser large enough to allow for use with an unfocused raw laser beam, as it would require an additional 100× increase in power or for new technology to be developed wherein the beam is already at focused diameters, thereby precluding the need for focusing optics.

In practice, we anticipate that multiple cuts will have to made in order for the laser cut to emulate what a knife girdling operation does to effectively terminate the phloem tissue and prevent the plant from simply healing over a very narrow surgical laser cut. Assuming the previous statements as a basis for the economics, an analysis is performed assuming two cuts are made by two lasers running in parallel. As the efficiency of CO_2 lasers run from 10%–20%, the proposed system would have a power budget per plant row of 88–170 kW-h per hectare^{-1}. Of note are previous literature reports for a propane-fired thermal defoliator using at least 745 kW-h per hectare^{-1} to achieve thermal defoliation of the cotton canopy [14,15]. Hence, the energy reduction potential for a stem girdling defoliation operation utilizing targeted laser girdling operation is significant and should be explored. However, the trial tests utilizing CO_2 laser to girdle the plants was almost universally ineffective. It is unknown whether this was due to the small sliver of untreated area on either side of the plant from the laser moving out of focus or if the surgical cuts were healing over too easily. Further work is necessary to explore these issues to determine if the laser could be utilized as an effective girdling tool. If it turns out that the cut simply needs to fully circle the stalk, then an engineering design will be needed that sweeps the laser to ensure the sides are also cut. Use of variable focus structure would also be beneficial to ensure that the stalks are always kept within the prime focal region. It should be recognized that these are not insignificant challenges; hence the first step should be to verify that laser girdling will achieve the desired defoliation response.

The report also covers the basic development of a laser system that could form the heart of a machine to perform this task on a field basis. The tests produced the required working parameters for a CO_2 laser to be able to successfully girdle typical deficit irrigated cotton plants grown in the West Texas region of the United States. The results of the study suggest that power control modulation of the laser would not be required to account for varying plant sizes. Results instead provided evidence that a fixed power level of 15–20 J mm^{-2} is the optimum laser power density to fully penetrate through the bark, thereby severing the phloem tissue without further damaging the plant.

The results of this study suggest that basic research can be conducted with a 100 W or larger CO_2 laser. For normal tractor travel speeds of 5 km h^{-1}, the laser power would have to be increased to 5 kW, assuming focusing optics are utilized. As the focusing optics have a narrow in-focus range of about the diameter of the main stalks, the use of focusing optics imparts significant precision requirements onto the operation. As only the main stalks of each plant are to be treated, the laser does not have to run continuously and could likely be on as little as 10% of the time. Thus, for a ten-row treatment implement, a 5–10 kW generator may be sufficient given the very low duty cycle. The estimated operational cost was presented, based on energy costs alone, and was found to be less than 100 kW-h per hectare^{-1}. Assuming no unforeseen complications, this suggests the potential for chemical-free cotton defoliation could be performed at as low a cost as \$0.88US per hectare^{-1}. Of importance is that this cost does not include tractor conveyance, depreciation or return on investment for capital cost of equipment. This technique has the potential to provide significant energy savings in comparison to the previous work that treated the entire canopy with hot air generated with propane burners, where the energy requirements were listed as running from 1200 to 2000 kW-h per hectare^{-1} [15]. It does, however, have some significant impediments to use that must be overcome if such a method is to become a viable commercial alternative to chemical applications.

Author Contributions: M. Pelletier, J. Wanjura and G. Holt conceived, designed the experiments, ran the tests, analyzed the data and wrote the paper.

Conflicts of Interest: The authors declare no conflict of interest.

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