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MOLECULAR BIOLOGY AND PHYSIOLOGY

1-Methylcyclopropene Effects on Field-Grown Cotton: Morphological Characteristics and Yield

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ABSTRACT

Upland cotton (*Gossypium hirsutum* L.) is an important socioeconomic crop throughout most of the southern U.S. In Texas, cotton is the lead cash crop and its productivity is often limited by abiotic stress events such as drought and elevated ambient temperatures. The objective of this study was to assess the effects of 1-methylcyclopropene (1-MCP) applications triggered by canopy temperature and forecasted ambient temperatures on field-grown cotton plants. Yield and crop morphological responses to 1-MCP applications were investigated in field studies conducted during the summers of 2012 to 2014 at the Texas A&M University Field Laboratory in Burleson County, TX. Positive effects of 1-MCP were found for fruit retention in 2013 and 2014 for both irrigated and dryland studies; however, a negative impact was found in the 2012 irrigated study. By harvest, 1-MCP applications had no effect on final cotton yield or fiber quality parameters. Applications of 1-MCP affected some morphological characteristics of cotton plants; however, it did not improve crop yield.

In the U.S., weather models predict an increase in air temperature ranging from 3 to 5 °C on average in the next 100 years assuming that the growth of world greenhouse gases emissions continues (MacCracken et al., 2003). Evidence also indicates the possibility of greater variability of rainfall patterns with extended drier periods (Allan and Soden, 2008; Easterling et al., 2000; Groisman and Knight, 2008; Karl and Trenberth, 2003). Soil moisture deficits along with high radiation and elevated temperatures pose the biggest limitation to the productivity of crops (Boyer, 1982; Idso et al., 1977). For cotton (*Gossypium hirsutum* L.) specifically, soil-available water is perhaps the primary yield-limiting factor across many production regions worldwide, and its impact on morphological, physiological, and yield parameters have been well documented (Ball et al., 1994; Carmo-Silva et al., 2012; Gerik et al., 1996; Pettigrew, 2004a, b; Quisenberry and Kohel, 1975; Turner et al., 1986; Van Iersel and Oosterhuis, 1996). High temperature stress is an aggravating factor that often occurs concomitantly to plant-available soil moisture deficits; its impact on boll retention, fiber quality, canopy growth, and other physiological impacts also have been documented (Lokhande and Reddy, 2014; Reddy et al., 1991; Zhao et al., 2005).

The combination of high temperature and drought stress produce significantly higher negative effects to crop growth and productivity compared to each stress separately (Blum et al., 1990; Prasad et al., 2011; Shah and Paulsen, 2003). High temperature stress can be defined as any temperature outside the upper bound of the thermal kinetic window (TKW), which represents the temperature range in which the apparent Michaelis-Menten constant (K_m) remains within 200% of the minimum value for optimum enzyme function. The term TKW as an indicator of optimum cotton performance was first coined by Mahan et al. (1987). The optimum temperature range of cotton is approximately 28 ± 3 °C (Burke and Wanjura, 2010), where important physiological, developmental, and biochemical processes are at peak performance. Exact understanding of how changes in climate patterns will affect plants and ecosystems is lacking. How agriculture will adapt to such changes also is largely unknown. It is, therefore of interest, to investigate potential means to mitigate the negative impacts of stresses on crop yield.

The hormone ethylene is known to be produced by almost all plant parts, from roots to stems, to leaves and flowers, and to be biologically active even in trace amounts. It is involved in a number of developmental and physiological processes in plants, including seed

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germination (Gniazdowska et al., 2010; Linkies and Leubner-Metzger, 2012), seedcoat development (Mohapatra and Mohapatra, 2006), production of volatile compounds (Dexter et al., 2007; Underwood et al., 2005), growth (De Grauwe et al., 2005; Foo et al., 2006; Malloch and Osborne, 1975), fruit ripening (Bapat et al., 2010; Goodenough, 1986), stress response (Fluhr and Mattoo, 1996; Pierik et al., 2007; Sharp and LeNoble, 2002), and abscission of vegetative and reproductive structures (Abeles and Leather, 1971; Jones et al., 1995; Morgan et al., 1992; Orzaez et al., 1999; Reid and Wu,1992; Steffens and Sauter, 2005). For ethylene to act, it must bind to a receptor that has a high affinity and specificity for ethylene (Sisler and Yang, 1984). At the cellular level, these receptors are located in great amounts in the endoplasmic reticulum and in smaller amounts in the plasmalemma (Bleecker, 1999; Chen et al., 2002; Evans et al., 1982).

The compound 1-methylcyclopropene (1-MCP) is an ethylene antagonist known to have a 10-fold higher affinity for ethylene receptors in the plant when compared to ethylene itself. Although effects seem to be transient and variable depending upon the plant and plant part treated, by competing for receptors 1-MCP delays and/or diminishes ethylene effects in plants (Sisler and Serek, 1997). Since its discovery, 1-MCP has been used efficiently in the fruit, vegetable, and ornamental flower markets to delay ripening and senescence during shipping and storage, ultimately leading to increased shelf life (Hofman et al., 2001; Jiang et al., 2001; Ku and Wills, 1999; Wills and Ku, 2002). In field production, 1-MCP can potentially help mitigate the negative impacts of stress and protect cotton yield, although available literature is limited and results are inconsistent. Kawakami et al. (2010a) and de Brito et al. (2013) conducted field trials and concluded that 1-MCP increased cotton yield under field conditions. On the other hand, da Costa et al. (2011b) reported that despite improved growth and yield components, no improvement in yield was found from 1-MCP. Chen et al. (2014) reported that 1-MCP treatment decreased membrane damage and increased chlorophyll content and photosynthetic efficiency of subtending leaves, but these benefits did not translate into higher yields. Under field conditions, possible 1-MCP treatment benefits could be curtailed by limitations in product delivery to the plants (e.g., concentration and time of exposure), timing of application, and presumably, the constant renewal of ethylene receptors (i.e., related to duration of effects). Theoretically, under field conditions 1-MCP has the potential to mitigate the negative impacts of stress and positively influence cotton yield.

The primary objective of this study was to assess the effects of 1-MCP applications triggered by canopy temperature and forecasted ambient temperature thresholds to help alleviate the negative impacts of high temperature stress on yield of field grown cotton plants. To achieve this, morphological parameters were monitored and analyzed at three distinct crop stages.

MATERIALS AND METHODS

Cultural Practices. Rainfed and irrigated field experiments were conducted side-by-side at the Texas A&M AgriLife Field Laboratory in Burleson County, TX, on a Weswood silt loam soil (fine-silty, mixed, superactive, thermic, Udifluventic Haplustepts), during 2012 to 2014 growing seasons. The field was equipped with a subsurface drip irrigation system. Drip lines were installed at a depth of 0.457 m, and emitters were spaced 0.457-m apart. Lines were spaced 1.02-m apart and were located at the center of each planting row. Water delivery was arbitrarily set at 80% evapotranspiration replacement for the irrigated trials, and amount of irrigation was adjusted based on specific crop stages following guidelines by Fisher and Udeigwe (2012) for cotton irrigation management for humid regions to account for crop phenology and changes in water demand.

Cotton (*G. hirsutum* cv. Phytogen 499 WRF) seeds were sown on 10 April 2012 and 9 April 2013 and 2014, at a rate of 108,000 seeds ha^{-1} in northwest to southeast oriented rows, spaced 1.02-m apart. Plant growth regulator applications consisting of a combination of cyclanilide and mepiquat chloride were applied as needed during the growing season. Harvest aids were applied when cotton plants exhibited approximately 60 to 70% open bolls. Management practices such as fertility, disease prevention, and weed and insect control followed guidelines provided by the Texas A&M AgriLife Extension service for the region.

Treatments and Experimental Design. The study plots were four rows wide, 9.73-m in length with a 3-m alley in between. Four treatments (including a control) were replicated four times and arranged in a randomized complete block design. Treatments were delivered to experimental plots by a four-row, small-plot, compressed air sprayer equipped with hollow-cone nozzle tips spaced at 51 cm, delivering 103 L ha^{-1}. Treatments consisted of 1-MCP at 25 g ha^{-1} of active ingredient (a.i.) with no adjuvants or surfactants. The 1-MCP formulation used was a soluble powder (3.8 % a.i.) mixed with water in the field immediately prior to application. Treatments were defined as: Control (C): No 1-MCP application; Smartcrop™ (S): 1-MCP application triggered by a canopy temperature of 28 °C accumulated for at least five consecutive hours; Ambient 35 °C (A35): 1-MCP application triggered by forecasted maximum daily temperature of 35 °C or higher for at least three consecutive days; Ambient 37.8 °C (A37.8): 1-MCP application triggered by forecasted maximum daily temperature of 37.8 °C or higher for at least three consecutive days. Treatments were initiated based on each trigger at the pinhead square stage and continued until plants reached open boll stage (Table 1.).

Table 1. Table shows timing of 1-methylcyclopropene (1-MCP) application based on different temperature thresholds (treatments). All applications were made using a powder formulation of 1-MCP at a single rate of 25 g a.i. ha^{-1} with a small-plot sprayer and occurred for both dryland and irrigated studies on the same dates

Treatment[z]	1-MCP Applications		
	2012	2013	2014
S	5-Jul	27-Jun	2-Jul
	5-Aug	11-Jul	24-Jul
		25-Jul	8-Aug
A35	5-Jul	11-Jun	10-Jul
	5-Aug	27-Jun	24-Jul
		11-Jul	8-Aug
		25-Jul	
A37.8	5-Aug	27-Jun	8-Aug
		11-Jul	
		25-Jul	

[z] Smartcrop (S), Ambient 35 °C (A35), and Ambient 37.8 °C (A37.8)

Canopy Temperature and Weather. SmartCrop™ (Smartfield Inc., Lubbock, TX) infrared thermometer (IRT) sensors were installed near the center of each plot to measure crop canopy temperature (CT) at 42, 59, and 64 days after planting (DAP) in 2012, 2013, and 2014, respectively. The IRT deployment occurred later in 2013 and 2014 due to unseasonably low temperatures following planting, which delayed initial crop growth. Sensors were mounted to a 2-m perforated pole to allow adjustment in sensor height, and a bracket maintained sensors at a fixed 45° angle from the soil surface. To account for crop growth, sensor heights were maintained at approximately 30 cm above the crop canopy. Canopy temperature data were collected every minute; 15-min averages were wirelessly transferred to a base station (SmartWeather™; Smartfield, Inc., Lubbock, TX), and then automatically uploaded to the CropInsight™ (Smartfield, Inc., Lubbock, TX) website (http://www.cropinsight.com/). Rainfall, ambient temperature, and wind data were collected by the SmartWeather station, which also served as a base station for the IRT sensors.

Soil and Leaf Water Potential. Soil water potential was measured using Watermark sensors (model 200SS, Irrometer Company, Inc., Riverside, CA) and the SmartProfile™ system (Smartfield, Inc., Lubbock, TX). Sensors were installed at 15-, 30-, and 61-cm depths, approximately 10 cm from the center of the row at 80, 66, and 92 DAP in 2012, 2013, and 2014, respectively. One set of sensors (three depths) was installed per study (i.e., dryland and irrigated). Pre-dawn leaf water potential (ψ_{wl}) was measured with a pressure chamber (PMS Instrument Co., Corvallis, OR) between 4:30 and 6:30 using the method described by Scholander et al. (1965). Three plants per plot were sampled using the third uppermost fully-expanded leaf, at three distinct crop stages: early bloom (EB), full bloom (FB), and open boll (OB). Approximately one third of the leaf petiole was cut using a razor at an approximate 45° angle. Leaves were placed within the chamber usually within 3 min of their removal from the plant. The pressure chamber was slowly pressurized at a rate of approximately 0.03 MPa s^{-1} as suggested by Turner (1988).

Plant Mapping. Plant mapping was conducted to assess the effects of 1-MCP application on plant growth and development. Six consecutive plants per plot, with the exception of very small plants (< one half of others, at any given growth stage) from either outside row, were removed from the field for plant mapping. Plant sampling was conducted at three distinct crop stages: EB, FB, and harvest (HA). Data was collected on plant height and reproductive structures, as well as number of vegetative, reproductive, and total mainstem nodes, from which height-to-node ratio was calculated. The data collection procedure and data input were handled according to Landivar (1992) and Landivar et al. (1993) using an Excel version of the Plant Map Analysis Program for Cotton software (PMAP).

Yield and Fiber Quality Characteristics. Two center rows of each plot were mechanically harvested using a custom two-row cotton spindle picker, John Deere (model 9910, Deere & Company, Moline, IL) that was modified for small-plot research. A subsample was collected and ginned on a small, 10-saw table-top gin with no lint cleaner to determine lint yield (gin turnout). Lint samples were analyzed for an array of fiber quality characteristics at the Fiber and Biopolymer Research Institute (Texas

Tech University, Lubbock, TX) utilizing the High Volume Instrument (HVI) method.

Statistical Analysis. Data were analyzed using JMP Pro, Version 11.0.0 (SAS Institute Inc., 2007). Analysis was performed on a yearly basis because significant Year x Treatment interaction occurred. Data were subjected to analysis of variance considering replication and treatment as random and fixed effects, respectively. Means were separated using Fisher's LSD at the 5% probability level. Means comparisons were made between treatments within each irrigation regime (dryland or irrigated) and data were combined over years whenever permissible.

RESULTS AND DISCUSSION

Total in-season rainfall were 503, 325, and 635 mm, for 2012, 2013, and 2014, respectively (Table 1). The 2013 growing season received only 64.6 and 51.2% of the rainfall compared to 2012 and 2014, respectively, for approximately the same time period. The average maximum temperature during all three seasons was greater than 31 °C, which indicated potential for high temperature stress (Fig. 1). Highest temperatures occurred between 12:00 and 17:00.

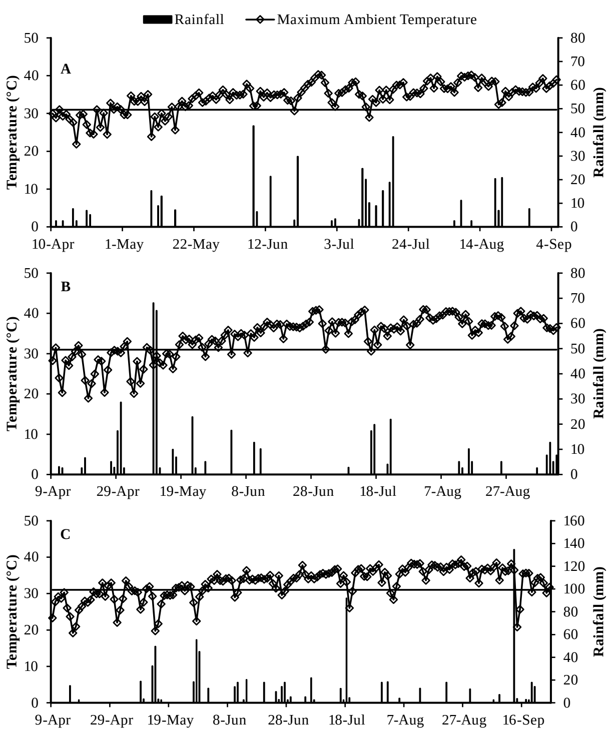

Figure 1. Daily maximum ambient temperature and rainfall during the season for (A) 2012, (B) 2013, and (C) 2014. Dashed horizontal lines represent 31 °C. Notice the difference in rainfall scale for 2014 compared to 2012 and 2013.

Differences in pre-dawn leaf water potential between the dryland and irrigated studies were found only at the OB stage for 2012 and 2014 (Figs. 2A, 2C) and indicated that well-distributed rainfall events were able to maintain adequate amounts of water in the soil profile during most of the growing season, even for the dryland studies (Table 2 and Figs. 2A, 2C). In contrast, during the 2013 season differences in leaf water potential were found throughout the growing season from EB through OB due to reduced rainfall (Table 2, Fig. 2B). It was evident at the OB stage that irrigated plots had higher leaf water potentials when compared to their dryland counterparts (Fig. 2). Higher leaf water potential (measured at midday) due to increased stomatal resistance 5 d after 1-MCP treatment have been reported in water-stressed cotton plants (Kawakami et al., 2010b), when compared to the untreated control also under water stress. Conversely, our results showed no impact of 1-MCP on pre-dawn leaf water potential between treatments, in any of the growth stages or years studied (Table 3).

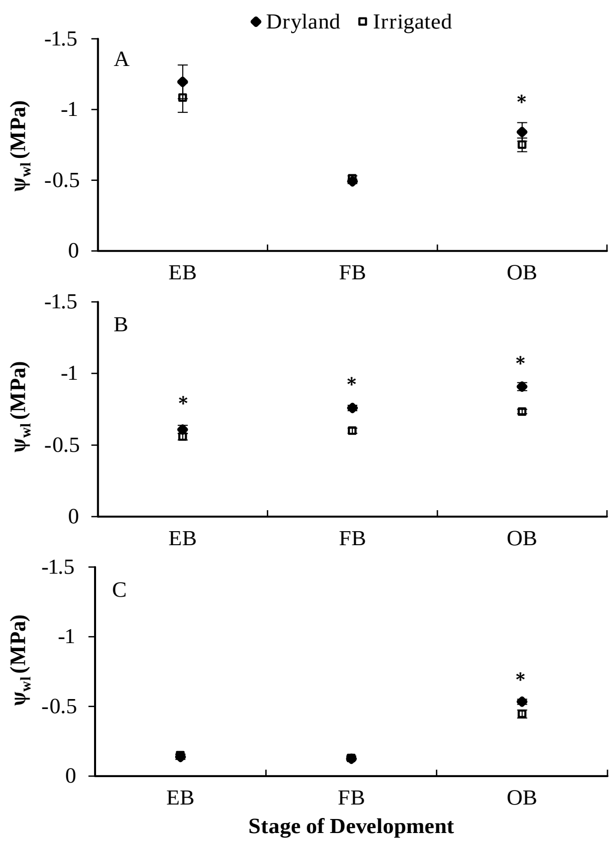

Figure 2. Pre-dawn leaf water potential (ψ_{wl}) measurements are shown for cotton grown during the summers of (A) 2012, (B) 2013, and (C) 2014. Values are averages of all four treatments combined within each growth stage (n = 48): early bloom (EB), full bloom (FB), and open boll (OB). Error bars represent ± SE, and * represents statistical significance between studies at the 5% probability level within each growth stage.

Table 2. Average soil water matric potential (ψ_m) measured at depths of 15, 30, and 61 cm for dryland (Dry) and irrigated (Irr.) studies. Total rainfall for each year of the study and their respective in-season accumulations are also shown

Year	ψ_m (Dry)			ψ_m (Irr.)			Rainfall	
	15 cm	30 cm	61 cm	15 cm	30 cm	61 cm	Total	Season
		MPa			MPa		mm	
2012	-0.47	-0.19	-0.27	-0.18	-0.11	-0.04	1,046	503
2013	-1.18	-0.41	-0.32	-0.35	-0.26	-0.10	998	325
2014	-0.44	-0.19	-0.14	-0.12	-0.07	-0.03	744	635

Table 3. Effect of 1-methylcyclopropene (1-MCP) on leaf water potential (ψ_{leaf}) at early bloom (EB), full bloom (FB), and open boll (OB) growth stages of field cotton grown during 2012, 2013, and 2014 under irrigated (IRR) and dryland (DRY) conditions. Values are averages of three samples and four replications per treatment (n = 12)

Year	Treatment[z]	ψ_{leaf} (EB)		ψ_{leaf} (FB)		ψ_{leaf} (OB)	
		IRR	DRY	IRR	DRY	IRR	DRY
				MPa			
2012	C	-1.08	-1.20	-0.51	-0.49	-0.75	-0.84
	S	-1.09	-1.30	-0.50	-0.54	-0.75	-0.88
	A35	-1.13	-1.23	-0.50	-0.55	-0.81	-0.92
	A37.8	-1.01	-1.19	-0.52	-0.51	-0.72	-0.83
	Sig. [y]	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
2013	C	-0.56	-0.61	-0.60	-0.76	-0.73	-0.91
	S	-0.56	-0.61	-0.61	-0.74	-0.75	-0.88
	A35	-0.57	-0.58	-0.56	-0.75	-0.73	-0.87
	A37.8	-0.53	-0.62	-0.57	-0.78	-0.75	-0.92
	Sig.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
2014	C	-0.15	-0.14	-0.13	-0.13	-0.45	-0.53
	S	-0.14	-0.15	-0.18	-0.15	-0.43	-0.48
	A35	-0.17	-0.15	-0.16	-0.13	-0.47	-0.46
	A37.8	-0.12	-0.14	-0.16	-0.16	-0.48	-0.49
	Sig.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.

[z] Control (C), Smartcrop (S), Ambient 35 °C (A35), and Ambient 37.8 °C (A37.8)

[y] Significance (Sig.) of differences between treatments at the 5% probability level. Not significant (n.s.)

Regardless of 1-MCP treatment, CTs were consistently higher in dryland plots when compared to those irrigated (Figs. 3A, 3B), and differences were more pronounced in the drier 2013 season than in the other growing seasons (2012 and 2014). Water-stressed plants exhibit elevated CTs compared to well-watered plants, as reported elsewhere (Idso et al., 1977; Jackson et al., 1977). Whereas average in-season CTs showed no effect of 1-MCP treatments on dryland plots (*p*-values 0.852, 0.293, and 0.287 for 2012, 2013, and 2014, respectively), under irrigated conditions, 1-MCP treatment did impact canopy temperatures (*p*-values 0.025, 0.027, and < 0.0001, for 2012, 2013, and 2014, respectively) in all three years of the study (Fig. 4B). The highest CTs were found for the S and A37.8 treatments in 2012 and 2013, respectively, whereas during the drier 2013 growing season, all 1-MCP treatments had higher CTs when compared to the untreated control. Under irrigation conditions at least one 1-MCP treatment displayed higher CT when compared to untreated control within the same study (Figs. 3A, 3B). Studies have shown that 1-MCP induces reduction in stomatal conductance (da Costa et al., 2011a), increased stomatal resistance (Kawakami et al., 2010b), and reduced respiration rates (Cefola et al., 2010). Although there is mounting evidence that 1-MCP effects are transient (da Costa et al., 2011a; Kawakami et al., 2010b; Su and Finlayson, 2012), it is possible that multiple applications were enough to affect in-season CT values for treated plots by temporarily reducing transpiration and thus plants' transpirational cooling, ultimately leading to higher CT. When growing cotton plants under well-watered conditions, da Costa and Cothren (2011a) reported a decrease in stomatal conductance and transpiration rates leading to higher CTs of 1-MCP-treated plants; the same effects were not evident on plants grown under water-deficit stress.

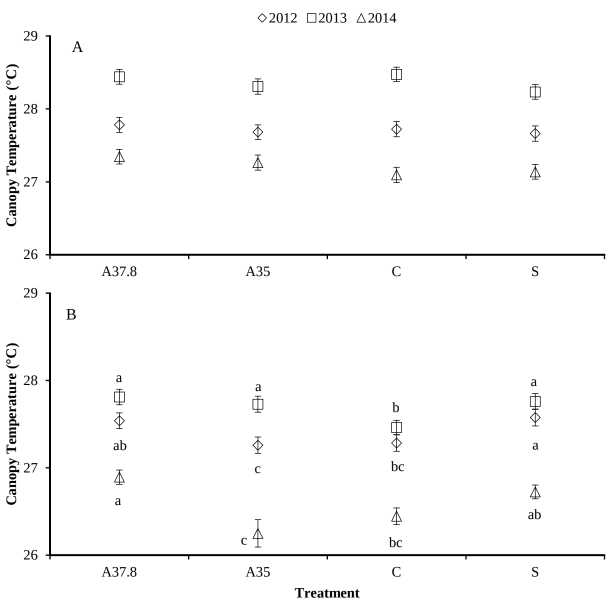

Figure 3. Effect of 1-methylcyclopropene (1-MCP) on different treatments for cotton grown during the summers of 2012, 2013, and 2014 under (A) dryland and (B) irrigated conditions. Values are shown as the average of daily canopy temperature throughout the season. Bars represent ± SE when greater than the symbols. Different letters within years represent significance at the 5% level of probability between treatments.

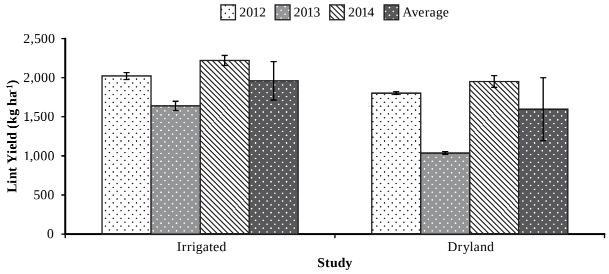

Figure 4. Average cotton yield across treatments for each of the three years studied. The 3-yr average is included for reference and shown on the far right of each study. Bars represent ± 1 standard deviation.

Because most cotton is indeterminate, it can compensate for both biotic and abiotic stresses that can occur throughout the growing season. Although this potentially can be beneficial in that plants might be able to recover from negative impacts of an early stress event, it complicates assessment of plant responses to treatments. Plant mapping analysis provides a good insight into the crop's morphological responses to adverse conditions that can negatively impact growth and yield. Cotton growth responses to 1-MCP applications in 2012, 2013, and 2014 are detailed in Tables 4, 5, and 6, respectively. Data showed that 1-MCP applications did impact at least one morphological characteristic in all three years studied. Those responses, however, were not consistent across years and did not necessarily translate into differences in fruit retention (FR) among treatments within studies and years.

Height-to-node ratio (H:N) is the ratio between total plant height (measured from the cotyledons to the top terminal of the plant) and total number of nodes (including both monopodial and sympodial nodes). It provides an integrated measure of the crop's stress level and source-sink balance (Kerby et al., 1998). Across years and growth stages, results showed that H:N ranged from 3.7 to 4.7 cm and 4.0 to 4.7 cm for the dryland and irrigated studies, respectively (Tables 4, 5, and 6). The 1-MCP treatments impacted H:N at harvest (HA) only for the irrigated studies in 2012 and 2013. In the 2012 irrigated study the S and A35 treatments had lower H:N when compared to C, whereas the A37.8 treatment although lower, was not statistically different than C or either of the two 1-MCP treatments (Table 4). In 2013, both S and A35 treatments had an H:N of 4.0 cm at harvest. These values were lower than both the A37.8 treatment (4.3 cm) and the C (4.2 cm), although differences were only significant against the A37.8 treatment (Table 5). In 2014, H:N was not affected by 1-MCP at harvest in the irrigated trial (Table 6). Across different years, H:N was not affected by 1-MCP treatment in any of the dryland trials at harvest. Although there is evidence that 1-MCP caused changes in the source-sink balance of the crop under conditions where water was not a strong limiting factor for productivity (irrigated studies in 2012 and 2013), it did not have any effect to the crop's H:N under dryland, more water-limiting conditions.

Table 4. Effects of 1-methylcyclopropene (1-MCP) application on morphological characteristics of cotton grown in 2012. Plant height (PH), height-to-node ratio (H:N), number of vegetative nodes (VN), number of reproductive nodes (RN), number of mainstem nodes (MSN), total number of reproductive structures (TRS), and final fruit retention (FR) were collected for both irrigated (IRR) and dryland (DRY) studies at three distinct growth stages: early bloom (EB), full bloom (FB), and harvest (HA). Values are average of 24 plants per treatment (TRT) (n = 24). Same letter in a column within a study and growth stage (GS) are not significantly different at the 5% level of probability. Control (C), Smartcrop (S), Ambient 35 °C (A35), and Ambient 37.8 °C (A37.8)

Year	Study	TRT	GS	PH	H:N	VN	RN	MSN	TRS	FR
				cm						(%)
2012	IRR	C	EB	83.7a	4.7a	4.8a	13.3a	18.1a	24.3a	98.7a
		S	EB	83.0a	4.5a	5.2a	13.2a	18.4a	24.7a	98.9a
		A35	EB	78.8b	4.6a	4.5a	12.8a	17.3a	24.5a	97.9a
		A37.8	EB	83.8a	4.6a	5.3a	12.8a	18.2a	24.2a	98.8a
2012	IRR	C	FB	89.4a	4.4a	5.6a	15.0a	20.5a	32.4a	62.2a
		S	FB	88.7a	4.1a	6.2a	15.5a	21.6a	35.2a	53.9b
		A35	FB	87.5a	4.3a	5.7a	15.0a	20.6a	34.7a	64.1a
		A37.8	FB	85.9a	4.3a	5.5a	14.6a	20.2a	32.8a	60.1a
2012	IRR	C	HA	96.4a	4.7a	5.5a	15.3a	20.8a	34.0a	44.0a
		S	HA	92.1b	4.4b	5.7a	15.5a	21.3a	33.1a	44.2a
		A35	HA	89.9b	4.3b	6.1a	14.9a	21.0a	33.3a	43.8a
		A37.8	HA	93.6ab	4.5ab	6.3a	14.7a	21.0a	28.6a	44.1a
2012	DRY	C	EB	82.8a	4.7a	5.7a	11.9a	17.6a	22.0a	96.4a
		S	EB	82.9a	4.7a	4.9a	12.7a	17.6a	25.6a	96.9a
		A35	EB	81.7a	4.5a	5.3a	12.8a	18.2a	24.5a	99.0a
		A37.8	EB	80.7a	4.6a	5.4a	12.4a	17.7a	22.6a	97.5a
2012	DRY	C	FB	88.0a	4.3ab	5.3a	15.2a	20.5a	31.7a	56.0a
		S	FB	88.3a	4.4a	5.6a	14.5a	20.2a	31.4a	58.3a
		A35	FB	89.2a	4.2ab	5.9a	15.4a	21.3a	33.3a	59.4a
		A37.8	FB	83.9b	4.0b	5.8a	15.0a	20.8a	31.2a	58.3a
2012	DRY	C	HA	88.5a	4.4a	5.8a	14.4a	20.2a	30.1a	44.9a
		S	HA	85.5a	4.2a	5.8a	14.4a	20.3a	28.7a	44.1a
		A35	HA	87.9a	4.3a	6.2a	14.3a	20.5a	30.3a	42.6a
		A37.8	HA	86.3a	4.3a	5.5a	14.5a	20.0a	29.7a	45.5a

Table 5. Effects of 1-methylcyclopropene (1-MCP) application on morphological characteristics of cotton grown in 2013. Plant height (PH), height-to-node ratio (H:N), number of vegetative nodes (VN), number of reproductive nodes (RN), number of mainstem nodes (MSN), total number of reproductive structures (TRS), and final fruit retention (FR) were collected for both irrigated (IRR) and dryland (DRY) studies at three distinct growth stages: early bloom (EB), full bloom (FB), and harvest (HA). Values are average of 24 plants per treatment (TRT) (n = 24). Same letter in a column within a study and growth stage (GS) are not significantly different at the 5% level of probability. Control (C), Smartcrop (S), Ambient 35 °C (A35), and Ambient 37.8 °C (A37.8)

Year	Study	TRT	GS	PH	H:N	VN	RN	MSN	TRS	FR
				cm						(%)
2013	IRR	C	EB	65.7a	4.5a	6.3a	8.3a	14.5a	14.3a	81.7bc
		S	EB	65.1a	4.3a	6.4a	8.8a	15.2a	16.4a	86.3ab
		A35	EB	65.8a	4.5a	6.2a	8.7a	14.8a	16.4a	92.4a
		A37.8	EB	68.8a	4.5a	6.2a	9.3a	15.5a	17.8a	79.2c
2013	IRR	C	FB	84.3a	4.5a	6.8a	12.2a	18.9a	24.3a	51.6a
		S	FB	86.9a	4.5a	6.4a	13.0a	19.4a	28.0a	49.3a

Table 5. (continued)

Year	Study	TRT	GS	PH	H:N	VN	RN	MSN	TRS	FR
				cm						(%)
		A35	FB	84.7a	4.4a	6.7a	12.8a	19.5a	28.5a	52.7a
		A37.8	FB	87.4a	4.5a	6.8a	12.9a	19.6a	26.6a	54.0a
2013	IRR	C	HA	86.5a	4.2ab	6.7a	13.8b	20.5b	25.6a	45.7a
		S	HA	88.3a	4.0b	6.5a	15.3a	22.2a	31.0a	42.1a
		A35	HA	89.1a	4.0b	7.1a	15.1a	22.2a	32.1a	42.0a
		A37.8	HA	91.8a	4.3a	6.8a	14.5ab	21.3ab	28.8a	46.2a
2013	DRY	C	EB	67.4ab	4.4a	6.6a	8.7a	15.3a	15.8a	78.0b
		S	EB	70.5a	4.6a	6.5a	9.0a	15.5a	14.7a	77.5b
		A35	EB	65.5b	4.3a	6.6a	8.6a	15.2a	15.7a	90.4a
		A37.8	EB	70.8a	4.5a	6.5a	9.3a	15.7a	18.3a	84.5ab
2013	DRY	C	FB	75.9a	4.3a	6.3a	11.5a	17.8a	23.6a	41.7a
		S	FB	74.3a	4.3a	6.6a	10.9a	17.5a	20.2a	36.8a
		A35	FB	78.8a	4.3a	6.8a	11.3a	18.1a	21.9a	40.2a
		A37.8	FB	73.8a	4.2a	6.7a	11.0a	17.7a	20.5a	40.4a
2013	DRY	C	HA	77.0a	3.9a	7.0a	12.9a	19.9a	25.0a	33.8a
		S	HA	77.8a	3.8a	6.6a	14.0a	20.6a	27.9a	31.0a
		A35	HA	77.3a	3.7a	6.7a	14.2a	20.8a	26.0a	31.4a
		A37.8	HA	76.3a	3.7a	7.1a	13.3a	20.4a	25.9a	37.0a

Table 6. Effects of 1-methylcyclopropene (1-MCP) application on morphological characteristics of cotton grown in 2014. Plant height (PH), height-to-node ratio (H:N), number of vegetative nodes (VN), number of reproductive nodes (RN), number of mainstem nodes (MSN), total number of reproductive structures (TRS), and final fruit retention (FR) were collected for both irrigated (IRR) and dryland (DRY) studies at three distinct growth stages: early bloom (EB), full bloom (FB), and harvest (HA). Values are average of 24 plants per treatment (TRT) (n = 24). Same letter in a column within a study and growth stage (GS) are not significantly different at the 5% level of probability. Control (C), Smartcrop (S), Ambient 35 °C (A35), and Ambient 37.8 °C (A37.8)

Year	Study	TRT	GS	PH	H:N	VN	RN	MSN	TRS	FR
				cm						(%)
2014	IRR	C	EB	60.0b	4.0a	6.6a	8.4a	15.0b	14.0a	79.5a
		S	EB	66.0a	4.1a	6.8a	9.3a	16.1a	16.4a	83.4a
		A35	EB	67.7a	4.2a	7.1a	9.0a	16.1a	15.9a	87.0a
		A37.8	EB	65.5a	4.1a	6.8a	9.4a	16.3a	16.0a	87.3a
2014	IRR	C	FB	91.0a	4.6a	7.2a	12.8a	20.0a	29.3a	85.4b
		S	FB	89.2a	4.7a	7.4a	11.8a	19.1a	26.1a	82.0b
		A35	FB	89.6a	4.6a	7.4a	12.2a	19.5a	29.8a	91.7a
		A37.8	FB	90.0a	4.7a	6.8a	12.4a	19.2a	28.7a	85.5b
2014	IRR	C	HA	105.8a	4.7a	7.8a	14.8a	22.6a	33.4a	43.4b
		S	HA	105.8a	4.6a	7.8a	15.2a	23.0a	33.3a	47.5ab
		A35	HA	103.4a	4.6a	7.1b	15.4a	22.5a	34.3a	46.8b
		A37.8	HA	107.3a	4.7a	7.2b	15.5a	22.6a	36.8a	52.3a
2014	DRY	C	EB	62.8a	3.9b	7.2a	9.0a	16.2ab	16.4a	85.4a
		S	EB	67.2a	4.2b	7.0a	9.2a	16.1ab	16.4a	86.2a
		A35	EB	67.9a	4.5a	7.3a	7.9b	15.3b	13.8a	84.2a
		A37.8	EB	68.0a	4.0b	7.3a	9.6a	16.8a	17.8a	85.4a

Table 6. (continued)

Year	Study	TRT	GS	PH	H:N	VN	RN	MSN	TRS	FR
				cm						(%)
2014	DRY	C	FB	78.4c	4.2a	7.3a	11.4a	18.7a	24.0a	80.6b
		S	FB	83.4ab	4.3a	7.1a	12.2a	19.3a	28.9a	88.8a
		A35	FB	87.4a	4.5a	7.3a	12.3a	19.6a	28.0a	83.6ab
		A37.8	FB	81.0bc	4.3a	7.6a	11.3a	18.9a	24.5a	85.1ab
2014	DRY	C	HA	90.4b	4.3a	7.7a	13.7a	21.3bc	28.5b	51.6a
		S	HA	97.8a	4.3a	7.3a	15.3a	22.6a	29.3b	47.9a
		A35	HA	98.4a	4.5a	7.4a	14.8a	22.2ab	36.7a	48.7a
		A37.8	HA	87.3b	4.2a	7.1a	14.0a	21.1c	28.1b	49.0a

By combining average plant mapping and yield data over studies and years, analysis demonstrated a high positive correlation between H:N and lint yield (LY) at harvest, such that the highest yields were found for plots with a H:N greater than 4.5 cm (Fig. 5). The number of bolls per unit area is the most important variable contributing to cotton yield (Boquet et al., 2004; Wu et al., 2005). For this study, this variable was indirectly assessed by analyzing FR for each plot. The FR value was calculated as the percentage of reproductive structures (squares, green bolls, and open bolls) retained on the plant at the time of measurement, to the total number of fruiting sites on both monopodial and sympodial branches (i.e., whole plant). Fruit retention was generally higher early, at EB, and decreased as the crop matured. Lowest FR values were found at HA and ranged across years from 42 to 52% and 31 to 51% for the irrigated and dryland studies, respectively, regardless of 1-MCP treatment. Not surprisingly, FR was highly correlated with final cotton yield at harvest (Fig. 6). A negative effect of 1-MCP application was detected at the FB stage in the 2012 irrigated study for the S treatment, which showed an 8% reduction in fruit retention when compared to the untreated control, at the same growth stage (Table 4). Interestingly, da Costa et al. (2011b) also found negative impacts of 1-MCP application on FR. The authors reported that two 1-MCP rates tested (25 and 50 g a.i. ha^{-1}) without surfactants produced the lowest boll retention values 50 d after treatment. Additionally, Chen et al. (2014) indicated lower FR in plants treated with 1-MCP at 10 g a.i. ha^{-1} when compared to untreated controls. In 2013, the A35 treatment was first sprayed with 1-MCP on 11 June (Table 2). Two weeks later when plots were sampled for the EB plant mapping there was a beneficial effect of 1-MCP on FR. When compared to their respective control plots, the A35 treatment had 10 and 12% higher FR at EB for the irrigated and dryland studies, respectively (Table 5). During the 2014 season, 1-MCP treatment benefited FR on the irrigated study for the A35 and A37.8 treatments at FB and HA, respectively, whereas under dryland conditions 1-MCP improved FR of the S treatment by 8% at FB when compared to the untreated control (Table 6). Except for the irrigated study in 2014, impact of 1-MCP treatment on FR values were nondetectable by the time plants reached maturity. Although difficult to ascertain, this is likely attributable to cotton's compensation abilities (Wilson et al., 2003).

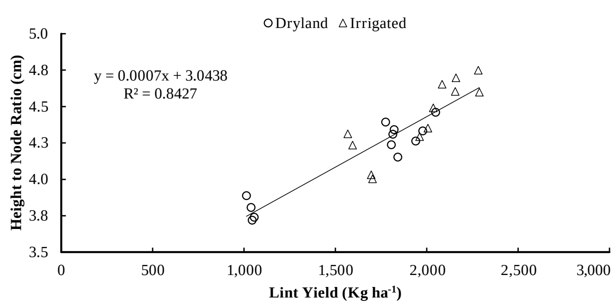

Figure 5. Relationship between height-to-node ratio and cotton yield at harvest, for cotton grown during 2012, 2013, and 2014. Data shown are a combination of irrigated and dryland studies across three years studied.

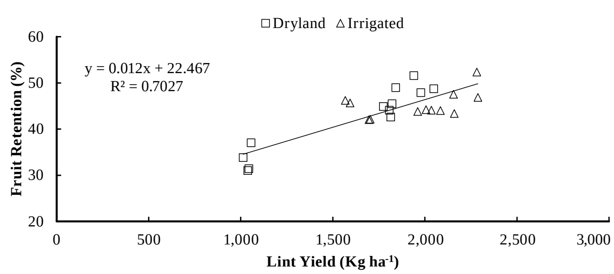

Figure 6. Relationship between fruit retention and final cotton yield at harvest, for cotton grown during 2012, 2013, and 2014. Data shown are a combination of irrigated and dryland studies across three years studied.

Table 7. Effect of 1-methylcyclopropene (1-MCP) application on final lint yield of cotton grown during 2012, 2013, and 2014. Values are average treatment yield for four replications (Reps) (n = 4) and are shown for both dryland (DRY) and irrigated (IRR) studies. Statistical significance (Sig.) at the 5% level of probability is shown. Non-significant (n.s.). Coefficient of variation (CV)

Treatment[z]	Reps	2012		2013		2014	
		IRR	DRY	IRR	DRY	IRR	DRY
		Lint Yield (Kg ha^{-1})					
C	4	2,083.8	1,774.4	1,593.7	1,012.5	2,159.3	1,939.3
S	4	2,006.1	1,805.8	1,702.5	1,037.8	2,155.2	1,977.9
A35	4	1,960.5	1,813.7	1,695.4	1,043.7	2,287.3	2,048.1
A37.8	4	2,035.2	1,820.8	1,567.7	1,055.5	2,281.6	1,841.5
CV		0.06	0.06	0.09	0.08	0.06	0.09
Sig.		n.s.	n.s.	n.s.	n.s.	n.s.	n.s.

[z] Control (C), Smartcrop (S), Ambient 35 °C (A35), and Ambient 37.8 °C (A37.8)

There were no differences in LY among 1-MCP treatments in any of the three years of the study post 1-MCP applications (Table 7). Yields ranged from 1,012 to 2,048 Kg ha^{-1} and from 1,568 to 2,287 Kg ha^{-1} for the dryland and irrigated studies, respectively (Table 4). Within each of the three years studied the irrigated study always had higher LY when compared to the dryland studies, as expected (Fig. 4). This difference was more pronounced during the drier 2013 season, when compared to 2012 and 2014. The 3-yr LY average was 1,598 and 1,961 Kg ha^{-1} for dryland and irrigated studies, respectively. Analysis of fiber quality characteristics as measured by the HVI method showed no effect of 1-MCP application on most fiber quality parameters such as micronaire, length, strength, and elongation.

CONCLUSIONS

Results of this study indicated that 1-MCP had little to no significant effect on morphological parameters of field grown cotton at different stages of crop development. The 1-MCP treatment had no impact on pre-dawn leaf water potential for either dryland or irrigated conditions. Average daily plant CT was affected by 1-MCP treatment when plants were grown under irrigation, but not under dryland conditions.

Both positive and negative effects of 1-MCP on fruit retention found during early and peak reproductive phases were mostly undetectable by harvest. Further, 1-MCP-treated plots showed no significant increase in LY when compared to the untreated control, in any of the three years studied and regardless of which temperature threshold was used to trigger applications.

In conclusion, the effects of 1-MCP applications based on the thresholds were variable and somewhat inconsistent. Ultimately, 1-MCP treatment effects were not enough to cause a significant increase in LY under the conditions tested.

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