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# Managing mepiquat chloride and plant density for optimal yield and quality of cotton

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ABSTRACT

The growth regulator mepiquat chloride (MC) is used in cotton production across the globe to control plant growth and maximize yield and quality of cotton. With the conversion from hand picking to mechanical harvesting in China, plant densities are increased, and more compact plants are required, leading to the need to reconsider MC application schedules. Experiments were carried out in 2009 and 2010 to identify optimal use schedules of MC at four plant densities: 3.0, 4.5, 6.0 and 7.5 plants $m^{-2}$. Eleven MC schedules were compared with respect to their effect on cotton yield and quality. Application of MC at squaring stage or at both squaring and flowering stages significantly improved cotton quality parameters: fiber length (by 1.7%) and fiber strength (by 2.8%) at all tested plant densities without significant loss of yields. However, average lint yield of all MC treatments over all densities and years was decreased by 4.6% due to a decrease in boll density and lint percentage which was only partly offset by an increase in boll weight. No effects on yield were also observed if MC applications were started at flowering stage, but such later starting application schedules only slightly improved fiber quality. The results suggest that use of MC at squaring or at both squaring and flowering stages is a viable strategy to improve cotton architecture, productivity and quality at high plant density in mechanized cotton production in the Yellow River cotton growing region in China.



## 1. Introduction

Cotton (*Gossypium hirsutum*) is a widely grown fiber crop across the globe. About 4 million hectares are grown annually in China, accounting for 20% of the world's cotton production (Dong et al., 2006b). The cotton plant is a perennial with indeterminate growth, continuing vegetative growth after fruiting has been initiated (Oosterhuis, 2001).

Smallholder farmers in the Yellow River and Yangtze River cotton growing regions still often grow cotton at low densities of around 3.5 plants $m^{-2}$, the advantage of low plant density being easier branch trimming (removal of vegetative branches) and hand harvesting. Mechanical harvesting is increasingly used, however, and it requires higher densities of 6.5–9.0 plants $m^{-2}$ in combination with a lower and more compact plant (Dong et al., 2006a). The plant growth regulator mepiquat chloride, N,N-dimethylpiperidinium chloride (abbreviated here as MC), can be applied to manipulate plant structure to facilitate mechanical harvesting at high plant density, and is widely used for this purpose across the globe (Cathey and Meredith, 1988; Reddy et al., 1992). There is limited empirical knowledge base on the optimum use of MC at high plant densities in the Yellow River and Yangtze River cotton producing regions, which are characterized by a hot and humid summer monsoon, which promotes abundant vegetative growth.

MC is considered advantageous for controlling plant structure under conditions that promote vegetative growth, which is detrimental to fiber yield and quality (Kerby, 1985; Constable, 1995; Oosterhuis and Egilla, 1996). Excessive vegetative growth results in more shade within the plant canopy, increased fruit abscission, and reduced yield (Guinn, 1974). Use of MC results in a shorter and more compact plant, lower leaf area index due to smaller leaf size (Reddy et al., 1990) and earlier maturity (York, 1983a; Kerby, 1985). MC affects plant structure through interference with hormonal

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**Table 1**
Monthly weather data of experimental site during cotton growing season in 2009 and 2010.

| Month | Average temperature (°C) | | | Precipitation (mm) | | | Sunshine hours (h) | | |
|---|---|---|---|---|---|---|---|---|---|
| | 2009 | 2010 | 30 years[a] | 2009 | 2010 | 30 years | 2009 | 2010 | 30 years |
| April | 15.6 | 11.4 | 14.5 | 21.3 | 27.3 | 18.8 | 268.8 | 244.8 | 241.7 |
| May | 21.8 | 21.7 | 20.4 | 25.9 | 34.3 | 32.6 | 294.4 | 282.5 | 289.2 |
| June | 26.3 | 25.3 | 25.5 | 102.6 | 27.5 | 68.9 | 307.0 | 256.1 | 203.2 |
| July | 26.8 | 28.4 | 26.7 | 106.8 | 86.3 | 194.7 | 257.1 | 244.7 | 118.3 |
| August | 24.5 | 24.9 | 25.5 | 214.2 | 195.8 | 121.1 | 195.5 | 198.8 | 206.3 |
| September | 19.7 | 20.0 | 19.9 | 53.8 | 52.3 | 46.8 | 174.7 | 184.0 | 186.2 |
| October | 14.6 | 12.7 | 13.9 | 12.6 | 9.3 | 21.9 | 224.0 | 200.9 | 149.4 |
| Total[b] | 21.3 | 20.6 | 20.9 | 537.2 | 432.8 | 504.8 | 1721.5 | 1611.8 | 1394.3 |

[a] Indicates an average over thirty years from 1979 to 2008.
[b] Indicates total values except for temperature which is averaged.

regulatory processes. As these processes respond in complex ways to growing conditions and plant density, optimal MC schedules are difficult to identify. Stewart (2005) suggested that the optimal time for applying MC in Louisiana cotton is shortly after observation of the first flower buds ('squares') or at early flowering. He et al. (1984, 1991) suggested for Chinese cotton applying MC at all early development stages including seedling stage, squaring stage, flowering stage and boll stage, but these studies were conducted at low plant densities.

Cotton lint yield is determined by boll density (the number of bolls per unit area), individual boll weight and the percentage of lint (fiber) per boll. MC and plant density can be used to manipulate these yield components (Stewart, 2005). The yield response to MC varies, however. Some studies showed a negative yield response to MC (Zhao and Oosterhuis, 2000) while other showed no response (Nichols et al., 2003; Pettigrew and Johnson, 2005), or a positive response, especially under conditions that favor excessive vegetative growth, such as surplus nitrogen (Kerby et al., 1982), high plant density (York, 1983b), late planting (Cathey and Meredith, 1988), or warm and humid growing conditions (Gwathmey and Clement, 2010).

Much research has been done to determine the optimum plant density for yield and quality in cotton. Some studies reported no significant relationship between yield and plant density (Hawkins and Peacock, 1973; Baker, 1976; Jones and Wells, 1998; Bednarz et al., 2000), whereas others demonstrated a yield reduction at very high or low density (Bridge et al., 1973; Smith et al., 1979). Optimal plant density depends on environmental factors such a s temperature, rainfall and crop management, with lower optimal density at conditions favoring lush vegetative growth such as in Yellow River (Dong et al., 2010, 2012) and Yangtze River regions of China, and higher optimal density in conditions under which vegetative growth is more restrained, such as in Northwestern continental China (Xinjiang), which is characterized by hot dry growing conditions.

Plant density and MC application affect the quality of cotton lint (Cathey and Meredith, 1988; Siebert and Stewart, 2006). Important quality traits are fiber length, fiber strength and micronaire. Longer fiber results in higher quality yarn. Fiber strength is measured by assessing the force at which a standard fiber sample will break in units of cN (centiNewton: 1 cN = 1.02 g) per tex (ICC standard which means fiber weight per 1000 m yarn). Micronaire measures the air permeability of the fibers and depends on their fineness (linear density), strength and maturity (degree of cell-wall development) (Saville, 2004). The textile industry prefers micronaire ranged from 3.7 to 4.2. When the micronaire is lower than 3.5, the fibers are thin and considered immature, while fibers with micronaire greater than 4.9 are considered too thick for textile.

Even though many studies have been done to identify optimal application schedules of MC, several questions remain unanswered for Yellow River cotton growing region in China: (1) What is the optimal MC schedule in the hot and humid monsoon climate of this region? (2) Are there differences in optimal MC schedules between low and high plant density, as found by York (1983b)? (3) What is the effect of MC on yield components and quality traits? (4) Are effects of plant density and MC consistent between years? The objective of this study is to answer these questions and identify optimal schedules of MC application at different plant densities in the Yellow River cotton growing region.

## 2. Materials and methods

### 2.1. Experimental design

Field experiments were conducted at Hejian experimental station (Lat. 38°24′ N, Long. 116°06′ E, Elev. 11 m) of China Agricultural University in Hebei province, China, in 2009 and 2010. The soil is a sandy loam with 10.3 g $kg^{-1}$ organic matter, 900 mg $kg^{-1}$ total N, 12.6 mg $kg^{-1}$ available P, and 163.5 mg $kg^{-1}$ available K in the top 40 cm of the soil profile. Climate is a temperate monsoon. Table 1 provides monthly average daily temperatures, total precipitation and sunshine hours. Average rainfall (1979–2008) was 505 mm during the cotton growing season (April to October) and total sunshine hours 1394 h. In 2009, rainfall was 537 mm, 6% above the long term average, and in 2010 433 mm, 14% below the long term average. Total sunshine hours were 1722 h in 2009, and 1612 h in 2010, 23 and 16% higher than the long term average, respectively.

Cotton was sown at a row distance of 90 cm on April 20 in 2009 and on April 25 in 2010. The cultivar was Guoxin3 (GX3), a high-yielding commercial Bt (*Bacillus thuringiensis*) transgenic upland cotton variety. Fertilizer was given according to common practice in both years: 225 kg $ha^{-1}$ N, 150 kg $ha^{-1}$ $P_2O_5$ and 225 kg $ha^{-1}$ $K_2O$. In each of the years, a single irrigation of 50 mm was applied, on July 10 in 2009 and on July 2 in 2010. The experiments were arranged in a split plot design with four replicates. Each plot consisted of six rows of cotton with a row length of 8 m.

The main plot treatment was plant density (3.0, 4.5, 6.0 and 7.5 plants $m^{-2}$). Plant distance within the row was 37.0 cm at a density of 3.0 plants $m^{-2}$, 24.7 cm at a density of 4.5 plants $m^{-2}$, 18.5 cm at a density of 6.0 plants $m^{-2}$ and 14.8 cm at a density of 7.5 plants $m^{-2}$.

The sub-plot treatment was MC application schedule. There were 11 MC schedules, including an MC free control (Table 2). MC was applied in one through four of four plant stages: (1) seedling stage (4 main stem leaves); (2) squaring stage (i.e. after first square and before first open flower; 10 main stem leaves); (3) flowering stage (i.e. after first open flower and before first open boll; 16 main stem leaves); and (4) boll stage (i.e. after first open boll; 22 main stem leaves). The dose at each stage was tailored to the plant size: 6, 18, 45 and 60 g $ha^{-1}$. The treatment code (T*xy*) represents the

**Table 2**
Application time and amount of mepiquat chloride (MC) in field experiments.

| Treatment code | Application time and dose (g $ha^{-1}$) of MC | | | | Total amount (g $ha^{-1}$) |
|---|---|---|---|---|---|
| | Seedling stage (DAS 30) | Squaring stage (DAS 50) | Flowering stage (DAS 65) | Boll stage (DAS 85) | |
| T00 | – | – | – | – | 0 |
| T11 | 6 | – | – | – | 6 |
| T22 | – | 18 | – | – | 18 |
| T12 | 6 | 18 | – | – | 24 |
| T33 | – | – | 45 | – | 45 |
| T23 | – | 18 | 45 | – | 63 |
| T13 | 6 | 18 | 45 | – | 69 |
| T44 | – | – | – | 60 | 60 |
| T34 | – | – | 45 | 60 | 105 |
| T24 | – | 18 | 45 | 60 | 123 |
| T14 | 6 | 18 | 45 | 60 | 129 |

The treatment code (T*xy*) represents the stage at which MC was applied for the first (*x*) and last (*y*) time. Seedling stage = 1, squaring stage = 2, flowering stage = 3, boll stage = 4. DAS is days after sowing. Seedling stage refers to 4–5 main stem nodes; squaring stage refers to 10–11 main stem nodes; flowering stage refers to 15–17 main stem nodes; boll stage refers to one week after cut-out (excision of the growing tip of the main stem in order to terminate its growth).

stage at which MC was applied for the first (*x*) and last (*y*) time, where seedling stage = 1, squaring stage = 2, flowering stage = 3, boll stage = 4. MC was applied with a $CO_2$ pressurized back-pack sprayer delivering 225 L $ha^{-1}$ at 104 kPa pressure.

### 2.2. Measurements

Yield was determined by two rounds of hand picking in the inner four rows of each plot, over a row distance of 7 m, thus excluding the border rows and plants in the first and last 50 cm of each row. The net harvested area was thus 25.2 $m^2$ per plot. The first harvest was made in the middle of October when approximately 60% of the bolls were open, and the second harvest was made at the end of October when at least 95% of the bolls were open. Seed cotton weight, including seed and lint (fiber), was determined after three days sun drying to water content of 12%. Cotton seed and fiber were separated using a roller ginning machine (made in Anyang, China). Lint and seed yields of the two harvests were summed before analysis. Lint percentage was computed as ginning outturn (lint), divided by total seed cotton yield. After measuring lint and seed weights, fiber quality was measured.

Boll density, boll numbers per unit area, was calculated as the sum of open bolls (including small amount of rotten bolls) and bolls large enough to be open under sun drying after final harvesting. Fifty bolls were collected randomly, choosing equally from the upper, middle and low fruit branches in each plot, to determine boll weight.

Lint quality was assessed according to the internationally accepted ICC standard (Anonymous, 2001). A fiber sample from each plot was assessed by the Supervision, Inspection and Test Center of Cotton Quality, Ministry of Agriculture, in Anyang, Henan province, using a High Volume Instrument (HVI-900). Fiber length was quantified by "2.5% fiber length", i.e. the average length of the 2.5% longest fibers. Fiber strength was measured by assessing the force at which a standard fiber sample will break in units of cN (centiNewton) per tex, where "tex" is a standard quantity of fiber (Saville, 2004).

### 2.3. Statistical analysis

Treatment effects on lint yield, yield components and fiber quality indices were analyzed with Analysis of Variance, using the General Linear Model procedure (GLM) in SPSS 17 (Chicago, IL, USA). MC application schedule and plant density were included as fixed factors in the ANOVA, plant density with four levels, and MC schedule with 11 levels (T00: control, T11, T12, T13, T14, T22, T23, T24, T33, T34, T44). Initially, an overarching analysis was conducted of the combined data of the two years, with year and replicate as random factors, and replicate nested within year. This analysis showed a significant year effect on all of the measured variables (Supplemental Table 1), and some interactions between plant density, MC and year. Therefore, we present analysis results for the two years separately. In these analyses, plant density and MC are fixed factors, and replicate a random factor. Interactions between plant density or MC and replicate were not significant and are not further reported (Supplemental Table 1). Presentation focuses on the main effects of plant density and MC in the two years. Means were separated using Duncan's Multiple Range Test at a significance level of 5%. Linear regressions were calculated between yield components (boll density and boll weight) and plant density.

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.fcr.2013.04.014.

The relationship between lint yield and density was further analyzed using a theoretical linear relationship between inverse plant lint weight and plant density (Bunting, 1971; Yahuza, 2011):

$$\frac{1}{w} = \alpha + \beta\,\mathrm{PD} \quad (1)$$

where *w* is the lint yield per individual plant (g/plant) and PD is plant density (plants $m^{-2}$). The regression model was fitted using data for each plot, with inverse lint yield per plant as dependent variable and PD as independent variable. In the regression model according to Eq. (1), MC was included as a factor with five levels according to applying amount: (1) no MC (T00); (2) MC in seedling and/or squaring stage (T11, T12 and T22); (3) MC applied up to flowering stage (T13, T23, and T33); (4) MC applied up to boll stage (T14, T24, T34); and (5) MC applied at boll stage only (T44). Separate analyses were conducted for the two years. The inverse of the parameter $\alpha$ is the estimated maximum lint yield per plant when plant density approaches zero, while the inverse of $\beta$ is the estimated maximum yield per unit area when plant density is very high.

## 3. Results

### 3.1. Lint yield

Plant density significantly affected lint yield across all MC treatments (Table 3). Lint yields were significantly higher at higher plant density of 4.5, 6.0 and 7.5 plants $m^{-2}$ than at the lowest density of 3.0 plants $m^{-2}$, especially in 2009 (Fig. 1a–c). There was a difference between the two years. In 2009, lint yield showed a linear increase with plant density, while this trend is weak in 2010.

Lint yield was significantly affected by MC application schedule in both years, but not by the interaction with PD (Table 3). The effect of MC was stronger in 2009, which was relatively wet, than

**Table 3**
Results of ANOVA for effects of mepiquat chloride (MC), plant density (PD), year and their interactions on lint yield, yield components and fiber quality index.

| Year | Effect | *df* | Lint yield | Boll density | Boll weight | Lint percentage | Fiber length | Fiber strength | Micronaire |
|---|---|---|---|---|---|---|---|---|---|
| 2009 | MC | 10 | $2.95^{**}$ | $3.30^{**}$ | $1.92^{*}$ | $5.96^{**}$ | $4.53^{**}$ | $1.00^{ns}$ | $1.18^{ns}$ |
| | PD | 3 | $19.95^{**}$ | $47.06^{**}$ | $9.95^{**}$ | $4.76^{**}$ | $3.22^{*}$ | $0.73^{ns}$ | $1.32^{ns}$ |
| | MC × PD | 30 | $0.60^{ns}$ | $0.75^{ns}$ | $1.29^{ns}$ | $0.54^{ns}$ | $1.25^{ns}$ | $0.82^{ns}$ | $1.11^{ns}$ |
| 2010 | MC | 10 | $4.85^{**}$ | $3.47^{**}$ | $2.73^{**}$ | $2.70^{**}$ | $3.50^{**}$ | $4.72^{**}$ | $1.92^{*}$ |
| | PD | 3 | $3.50^{*}$ | $112.92^{**}$ | $40.97^{**}$ | $4.29^{**}$ | $0.16^{ns}$ | $0.93^{ns}$ | $15.10^{**}$ |
| | MC × PD | 30 | $0.93^{ns}$ | $5.23^{**}$ | $0.60^{ns}$ | $1.18^{ns}$ | $0.86^{ns}$ | $1.44^{ns}$ | $1.50^{ns}$ |
| Two years | MC | 10 | $5.23^{**}$ | $2.56^{**}$ | $3.13^{**}$ | $5.00^{**}$ | $6.28^{**}$ | $3.83^{**}$ | $1.28^{ns}$ |
| | PD | 3 | $17.2^{**}$ | $106.23^{**}$ | $43.07^{**}$ | $3.35^{*}$ | $2.00^{ns}$ | $0.41^{ns}$ | $12.40^{**}$ |
| | Year | 1 | $140.77^{**}$ | $29.13^{**}$ | $89.91^{**}$ | $9.78^{*}$ | $25.64^{**}$ | $1.87^{ns}$ | $4.50^{ns}$ |
| | MC × PD | 30 | $0.85^{ns}$ | $1.32^{ns}$ | $0.93^{ns}$ | $0.79^{ns}$ | $1.19^{ns}$ | $1.32^{ns}$ | $0.85^{ns}$ |
| | MC × Year | 10 | $2.73^{**}$ | $3.06^{**}$ | $1.50^{ns}$ | $1.52^{ns}$ | $1.80^{ns}$ | $1.72^{ns}$ | $1.76^{ns}$ |
| | PD × Year | 3 | $7.84^{**}$ | $8.77^{**}$ | $6.86^{**}$ | $5.17^{**}$ | $1.37^{ns}$ | $1.25^{ns}$ | $6.00^{**}$ |

*F* values and significance levels:
* $P < 0.05$.
** $P < 0.01$.
ns: no significance are given.

in 2010, which was drier. Lint yield in MC treated cotton, averaged over densities and years, was 4.6% lower than in the control. Only those treatments with higher MC applying dose e.g. T13, T14, T24 showed a significant decrease in lint yields comparing to the MC free control (Fig. 1 and supplemental Table 1).

MC and PD did not significantly interact. However both of them significantly interacted with year, which implied that climate factors, e.g. rainfall, greatly affected the application of MC and PD.

Cotton lint yield was described well by the linear relationship between inverse plant lint weight and density given by Eq. (1), while MC treatments were grouped by applying dose. As shown in Table 4, the potential yield under intraspecific competition was significantly lower in MC treatments than in the control. The maximum yield per plant ($1/\alpha$) was not significantly different between treatments. The actual yields (1.2–1.7 ton $ha^{-1}$) were around 63% of potential yields under intraspecific competition (yield at optimal plant density) for all treatments (3.1–4.7 ton $ha^{-1}$, Table 4).

### 3.2. Yield components

Boll density was significantly ($P < 0.01$) affected by plant density (Table 3). In both years, it was highest at 7.5 plants $m^{-2}$, and lowest at 3.0 plants $m^{-2}$ (Fig. 2). Good linear relationships were found between boll density and plant density across all MC treatments: $y = 8.54x + 78.4$ ($R^2 = 0.99$) in 2009, and $y = 8.20x + 71.86$ ($R^2 = 0.78$) in 2010, where $y$ = boll density and $x$ = plant density.

Boll density (bolls $m^{-2}$) was also significantly affected by MC (Table 3), which was significantly lower in MC treatments e.g. T14

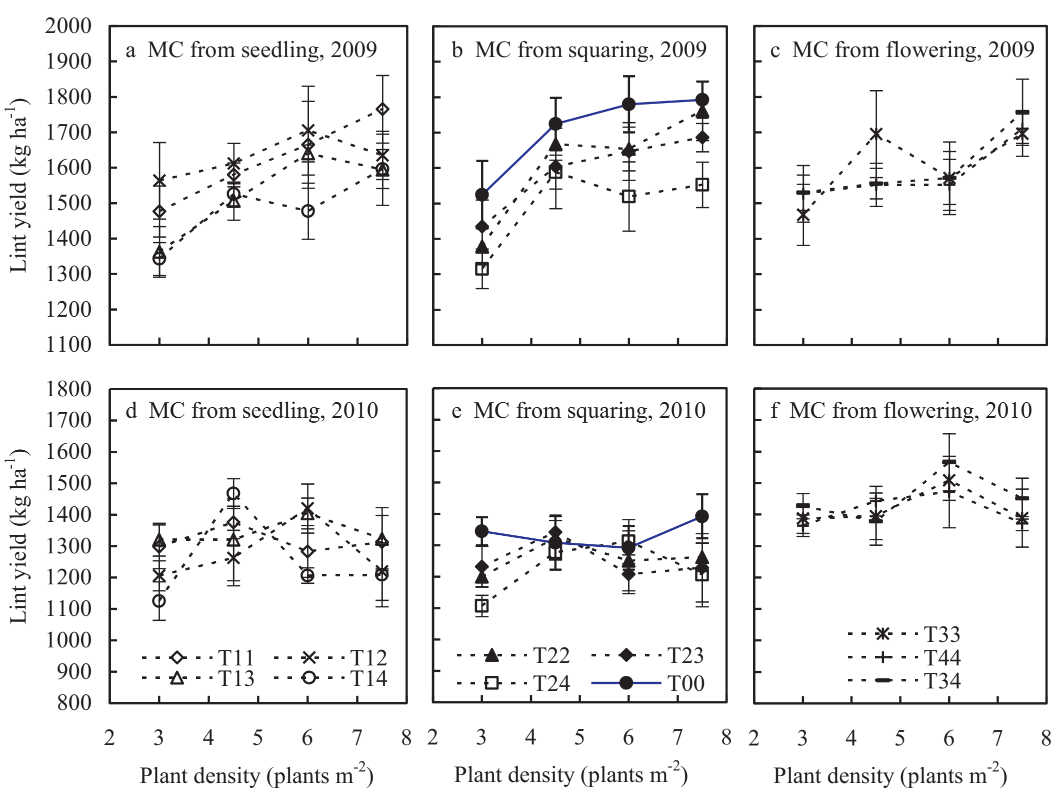


**Fig. 1.** Effect of plant densities and mepiquat chloride (MC) schedule on lint yield in 2009 and 2010. The MC-free control (T00) is shown with solid lines and MC treatments are shown in dotted lines. The treatment code (T*xy*) represents the stage at which MC was applied for the first ($x$) and last ($y$) time (cf. Table 2).

**Table 4**
Regression parameters of the relationship between plant density (PD) and inverse plant weight, as affected by mepiquat chloride (MC). MC treatments were grouped according to plant stages in which MC application was terminated. The relationship between yield and density given by the equation $w^{-1} = \alpha + \beta \times PD$, where $w$ = weight per plant and PD = plants $m^{-2}$. The values of the parameters in this model give an indication of potential yield per plant when free from competitive stress ($\alpha^{-1}$) and of the potential lint yield under intraspecific competition ($\beta^{-1}$).

| Year | MC treatment | MC applying time | MC amount ($g\,ha^{-1}$) | $\alpha^{-1}$ ($g\,plant^{-1}$) | $\beta^{-1}$ ($g\,m^{-2}$) |
|---|---|---|---|---|---|
| 2009 | T00 | No MC | 0 | 575.7a | 465.5a |
| | T11, 12, 22 | MC until seedling/squaring | 6, 18, 24 | 601.5a | 440.6b |
| | T13, 23, 33 | MC until flowering | 45,63, 69 | 555.8a | 428.3c |
| | T14, 24, 34 | MC until boll stage | 105,123,129 | 1033.0a | 402.3d |
| | T44 | MC only at boll stage | 60 | 559.4a | 432.1bc |
| | | Marginal SE | | 158.6 | 5.4 |
| 2010 | T00 | No MC | 0 | 893.0a | 344.5a |
| | T11, 12, 22 | MC until seedling/squaring | 6, 18, 24 | 1531.6a | 307.2b |
| | T13, 23, 33 | MC until flowering | 45,63, 69 | 2899.3a | 317.1b |
| | T14, 24, 34 | MC until boll stage | 105,123,129 | 1031.7a | 322.0ab |
| | T44 | MC only at boll stage | 60 | 1280.4a | 346.2a |
| | | Marginal SE | | 863.5 | 8.1 |
| *P*-value | MC applying time | | | 0.237 | 0.634 |
| | Year | | | 0.000 | 0.100 |
| | MC application time × Year | | | 0.009 | 0.489 |

Same small letter indicates no significance at $a = 0.05$.

than in MC free control T00 (Fig. 2). No interaction between MC and PD was found, while both MC and PD significantly interacted with the year.

The weight of individual bolls ($g\,boll^{-1}$) was significantly ($P < 0.01$) affected by plant density (Table 3), showing a linear decrease (Fig. 3a and b). The linear regression between boll weight and plant density across all MC treatments was $y = -0.10x + 6.74$ ($R^2 = 0.82$) in 2009, and $y = -0.21x + 6.61$ ($R^2 = 0.99$) in 2010. The interaction between plant density and year was significant ($P < 0.01$). The slope of the linear regression was larger in 2010, which was mainly caused by draught in this year.

Boll weight was significantly affected by MC (Table 3). Boll weight increased with MC dose (Fig. 3c and d), however, it was not continuously increased when MC dose was high (from T13 to T14) in 2010. There were no interactions with plant density or year (Table 3).

The effect of plant density on lint percentage significantly interacted with year (Table 3), which was not consistent due to weather differences between two years (Fig. 4). Lint percentage was significantly affected by MC (Table 3), which was markedly reduced at high MC e.g. T14, as compared to the control T00 (Fig. 4). MC application showed no significant interaction with plant density and year (Table 3).

### 3.3. Fiber quality

Fiber length was significantly affected by MC treatments ($P < 0.01$), but not significantly affected by plant density (Table 3). There were no any interactions between year, MC and plant density. Fiber length increased with MC dose for those treatments with MC starting from seedling (Fig. 5a and b) or squaring stages (Fig. 5b and e), but for MC starting from flowering stage (Fig. 5c and f) was not significantly different with the control T00.

Fiber strength was not significantly affected by plant density, but was significantly affected by MC without interactions with year and PD (Table 3). The fiber strength was increased with MC dose (Fig. 6). The increasing rate (slope of line) of fiber strength was higher for early MC applications (seedling, squaring and flowering stages) than for later application (boll stage).

Micronaire clearly decreased with plant density in 2010, but not in 2009 (Fig. 7). The interaction between plant density and year was significant (Table 3). MC application did not significantly affect micronaire (Table 3). There was no consistent relationship between micronaire and MC treatment (Fig. 7).

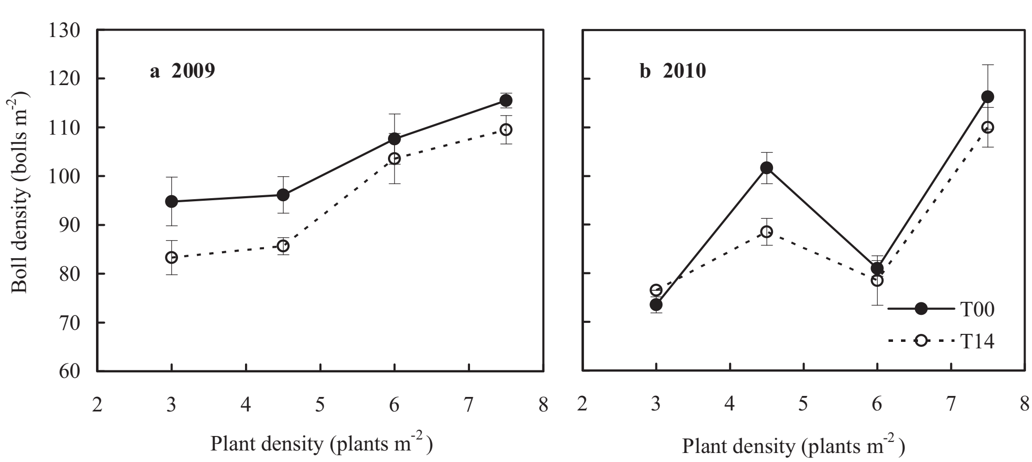


**Fig. 2.** Relationship between boll density and plant density for two mepiquat chloride (MC) treatments in 2009 and 2010. T00 and T14 indicate MC-free treatment and applying MC 4 times from seedling to boll stages respectively.

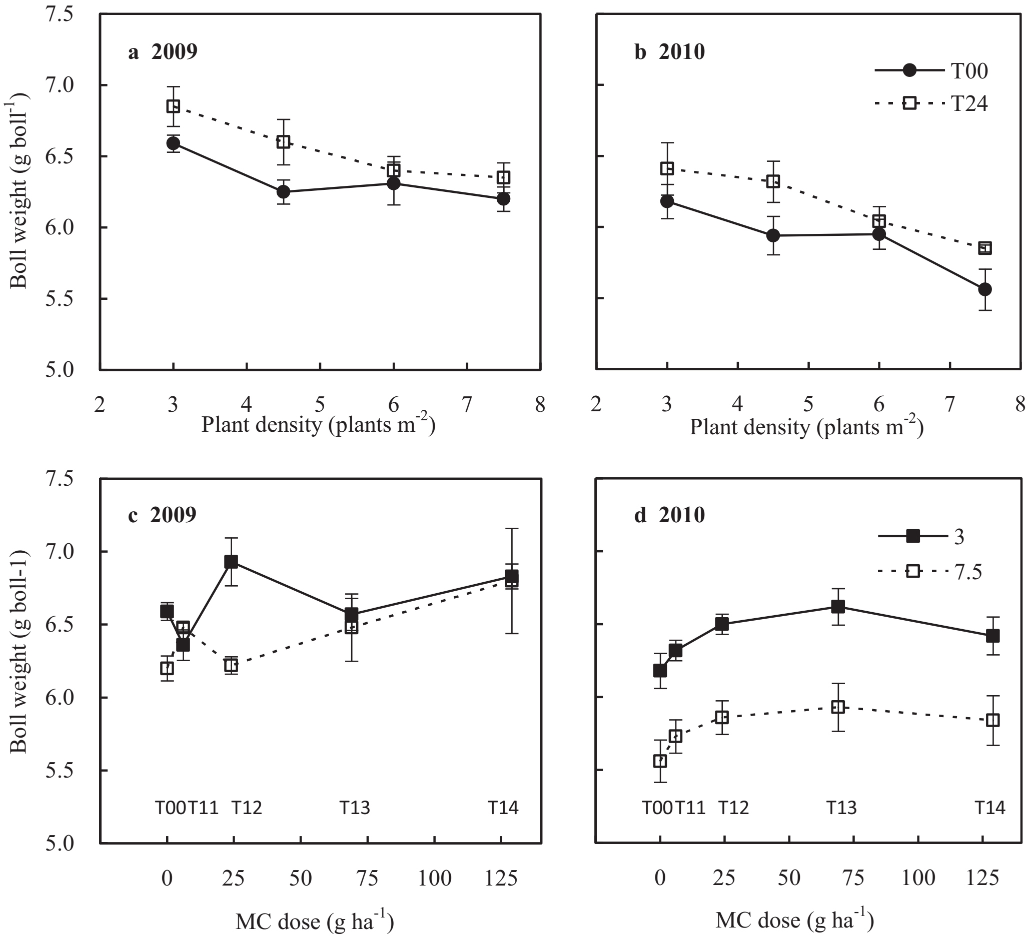


**Fig. 3.** Relationship between boll weight and plant density (a and b) and mepiquat chloride (MC) dose (c and d) in 2009 and 2010. For treatment coding, see Table 2.

## 4. Discussion and conclusions

The optimal MC schedule in Yellow River cotton growing region, was to apply MC at squaring or at both squaring and flowering stages (T22 and T23), by which MC significantly increased fiber quality by 1.7% for fiber length and 2.8% for fiber strength without significant loss of yield. No effects on yield were also observed if MC applications were started at flowering stage, but such later starting application schedules only slightly improved fiber quality.

There were small differences in optimal MC schedules between low and high plant density, which is not consistent to the finding of York (1983b), which reported a positive response at high PD.

Our results showed that MC decreased boll numbers per unit ground area (boll density) while PD increased it. The boll weight decreased by PD but increased by MC. The effects of MC and PD

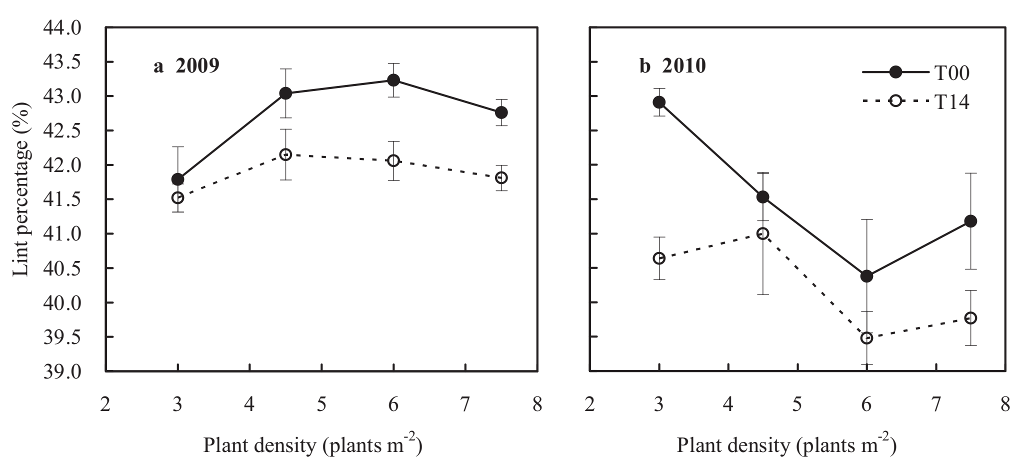


**Fig. 4.** Relationship between lint percentage and plant density for two mepiquat chloride (MC) treatments in 2009 and 2010. T00 and T14 indicate MC-free treatment and applying MC 4 times from seedling to boll stages respectively.

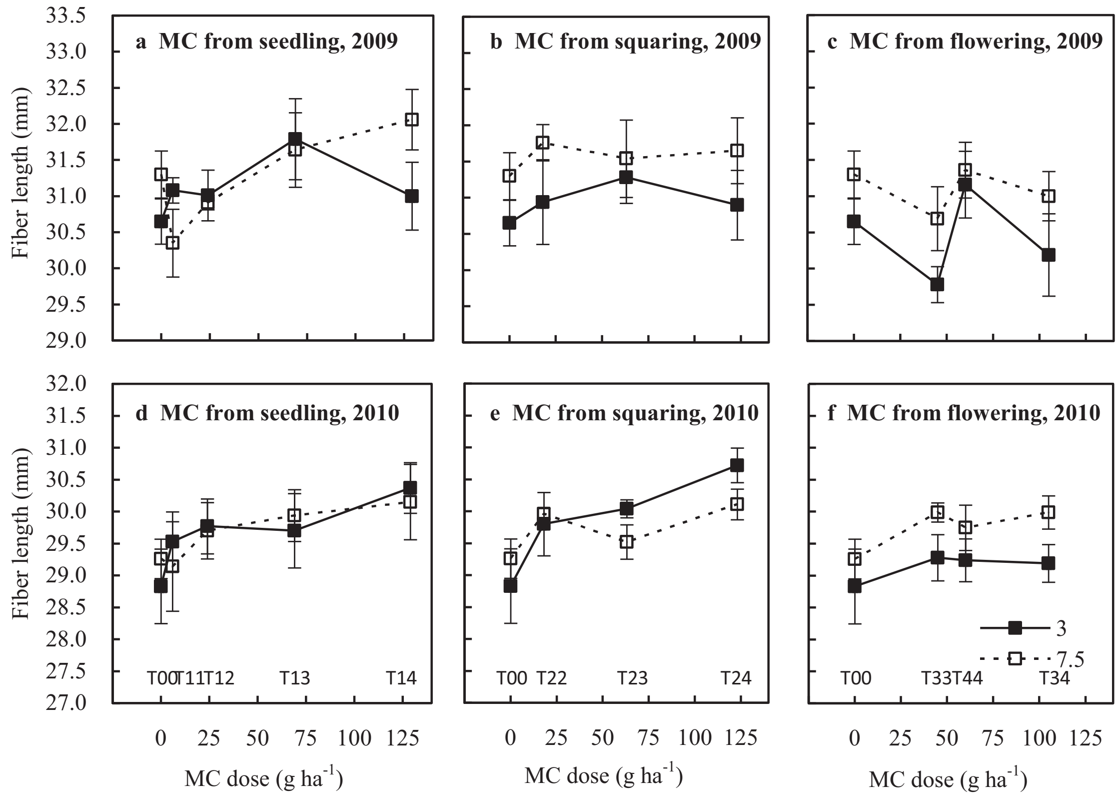


**Fig. 5.** Relationship between fiber length and mepiquat chloride (MC) dose at two plant densities in 2009 and 2010. For treatment coding, see Table 2.

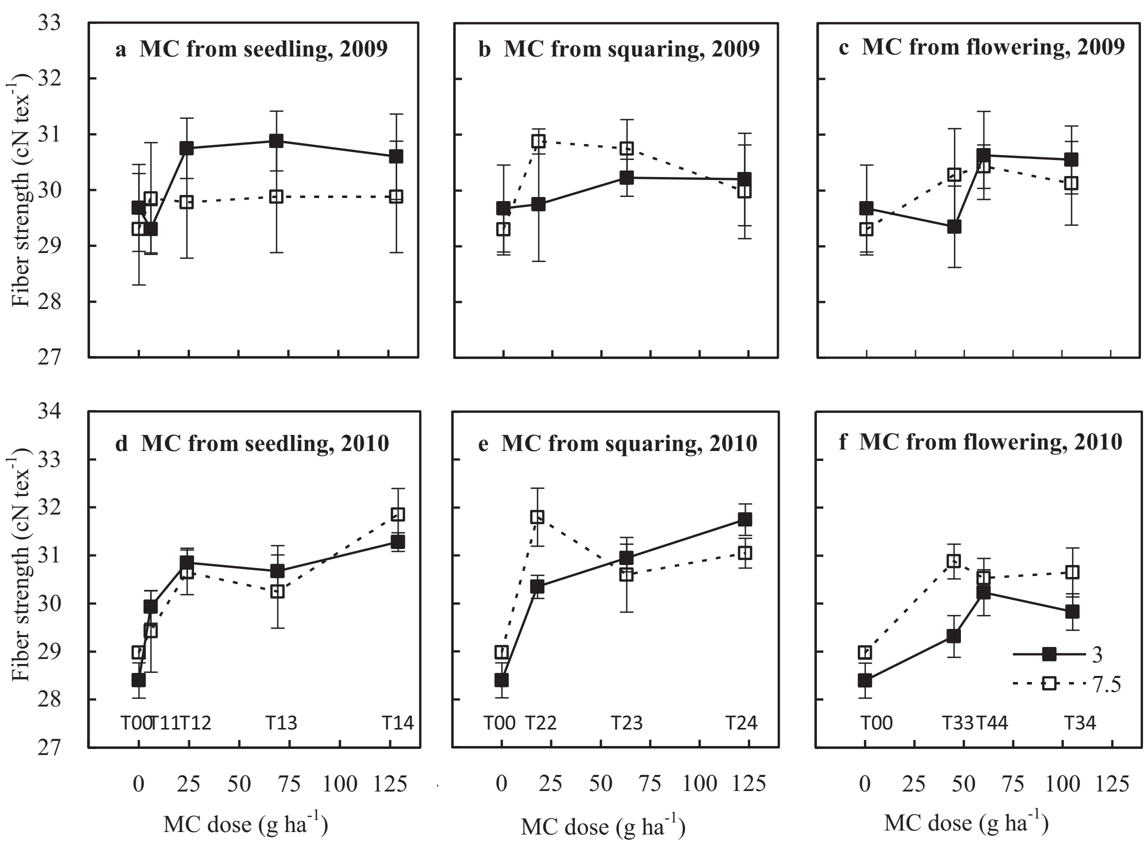


**Fig. 6.** Fiber strength affected by mepiquat chloride (MC) dose and starting time at two plant densities in 2009 and 2010. For treatment coding, see Table 2.

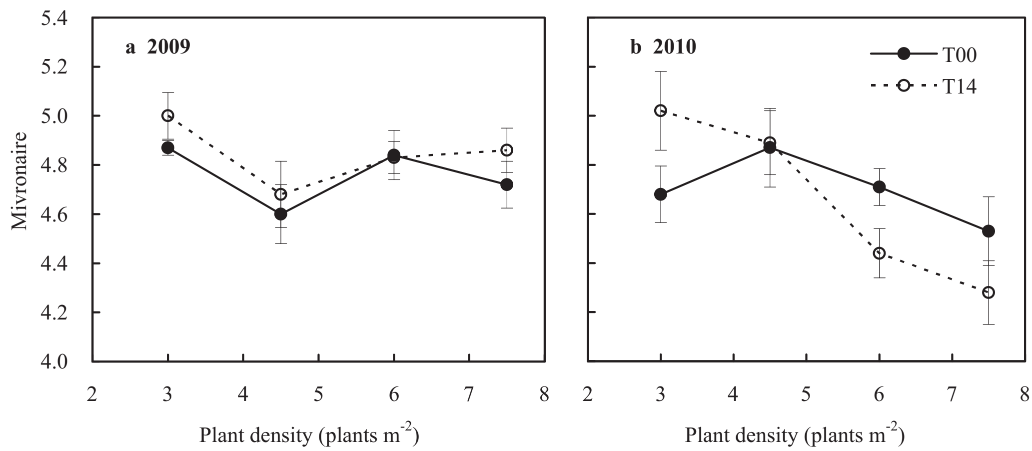


**Fig. 7.** Relationship between micronaire and plant density for two mepiquat chloride (MC) treatments in 2009 and 2010. T00 and T14 indicate MC-free treatment and applying MC 4 times from seedling to boll stages respectively.

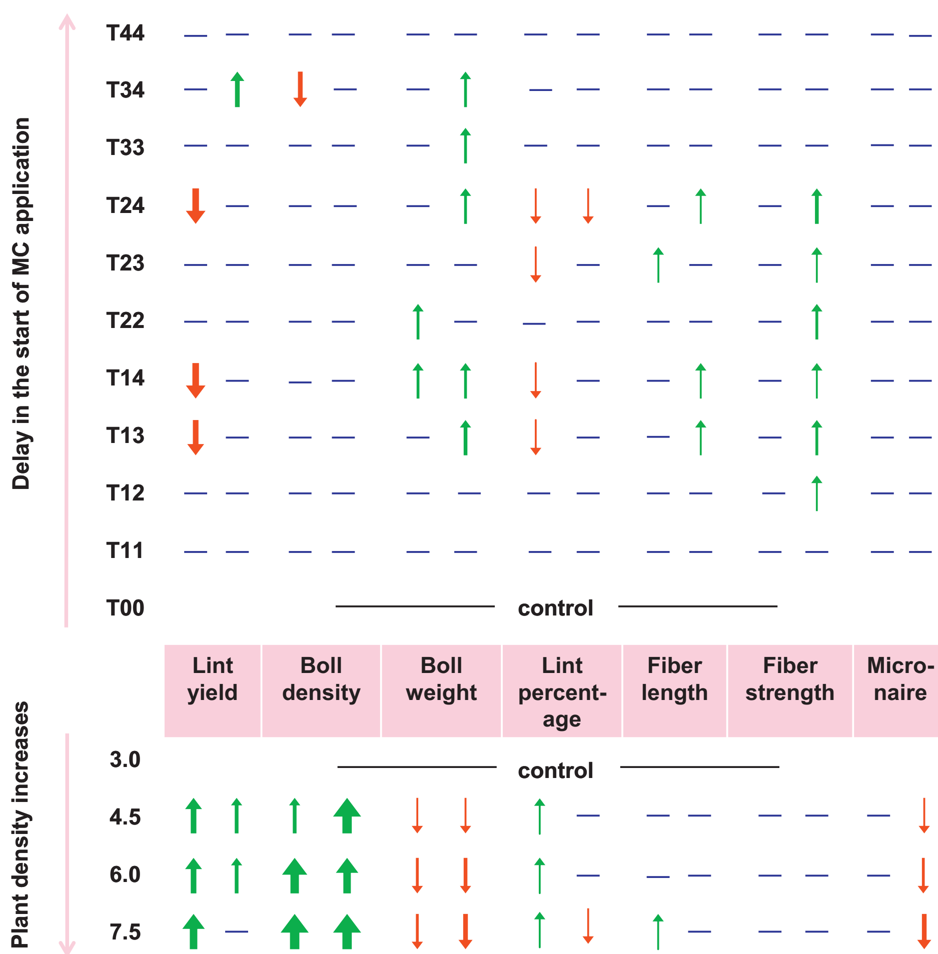


**Fig. 8.** The schematic responses of cotton yield and quality to mepiquat chloride (MC) and plant density (PD). T*xy* represents the stages at which MC was applied for the first (*x*) and last (*y*) time. Seedling stage = 1, squaring stage = 2, flowering stage = 3, boll stage = 4. Red arrows indicate a significant decrease compared to no MC application or lowest plant density (3.0 plants $m^{-2}$) and green arrows indicate a significant increase. The '—' indicates no significant response. Arrow thickness represents the magnitude of the increase or decrease. The control treatment is used are reference for MC effects, while the plant density of 3 plants $m^{-2}$ is used as reference for plant density effects. Arrows or short lines in each box refer to 2009 and 2010, respectively.

were additive. The results suggested that the negative effects of plant density could be partially compensated by positive effects of MC and vice versa.

The effects of plant density and MC were not consistent between years due to difference of weather conditions, e.g. rainfall during cotton rapid growth period.

### 4.1. Effects of MC on yield and yield components

In 2009, application of MC with high dose (T13, T14 and T24), the cotton lint yield significantly decreased compared to the control, whereas single boll weight was significantly increased. This is because the boll density and lint percentage decreased compared to no MC. In 2009 and 2010, rainfall was 107 and 86 mm during cotton squaring stage and beginning of flowering stage (July) respectively, which is 45% and 56% less compared to the 30 year's average of 195 mm. A likely reason for the sensitivity of lint yield to MC application was the reduction of carbohydrate production caused by severely decreased canopy size by MC due to the low rainfall during rapid growth period (squaring and flowering stages). This corroborates Xi et al. (1981), who indicated that applying MC at early stages of development (seedling and squaring stage) results in less vegetative growth.

Previous studies reported that MC might decrease cotton leaf area, depending on the rate of application and the stage of development of the plant (Reddy et al., 1990; Fernandez et al., 1991). The application of MC decreased shoot length but had no significant effect on dry matter production (De Almeida and Rosolem, 2012). In our study, the maximum yields (yield at optimal plant density) under intraspecific competition of applying MC at different times and doses also showed a significant decrease compared to the control, which suggests that the plants with MC application had lower competitive and compensatory abilities, probably due to the smaller leaf area and compact structure.

Applying MC increased boll weight but decreased the lint percentage, which implies that the MC do not have an equal effect on improving both fiber and seed weight. This indicates that applying MC changed carbohydrate partitioning ratio in favor of seed rather than fiber. Thus, MC will improve seed quality by means of enhancing seed weight, which was good for germination.

### 4.2. Interaction between the effects of MC and plant density on yield

No significant interactions between MC and plant density were found in this study, corroborating results of Siebert and Stewart (2006). An interaction between MC and PD was suggested by York (1983b). However, our results for effects of MC and PD on yield component (boll density and boll weight) showed an additive effect rather than an interaction effect. The ANOVA results showed also no significant interaction across two years. The experimental years were very dry at cotton rapid growth period (July), in which the rainfall was 45% to 56% less than historical average. Thus, the effect of MC was suppressed by dry weather.

The reason for the lack of a significant interaction between plant density and MC might be due to the insufficient plant density. In our study the highest density was 7.5 plants $m^{-2}$, which may not have been high enough to compensate the loss of boll numbers by applying MC. Total boll density were decreased by 5.0 bolls $m^{-2}$ by using MC at squaring and flowering stages. The boll density would be increased 8.3 bolls $m^{-2}$ (averaged slopes of linear regression lines between boll and plant density) by increasing plant density by 1.0 plant $m^{-2}$. Thus, to compensate the boll loss due to MC application, the optimal plant density with MC would be increased by 0.6 plants $m^{-2}$ (5.0 bolls $m^{-2}$ divided by 8.3 bolls per plant) to at least 8.1 plants $m^{-2}$, assuming linear extrapolation is valid in this case.

### 4.3. Effects of MC and plant density on fiber quality

In other studies, the effects of MC on fiber properties have been erratic (Kerby, 1985; York, 1983a, 1983b). In our study, MC application significantly improved fiber length and strength without increasing micronaire, and therefore cotton fiber quality as a whole. Cotton fiber length across all MC treatments at highest plant density was significantly higher than that at lowest density in 2009. This is likely due to increased early formation of bolls at low positions in the plant at high plant density, since low plant densities induce more late-season bolls, which exhibit poorer fiber properties due to insufficient heat units (Jones and Wells, 1998). However, other factors such as genotype and agronomic management affecting fiber quality (Bednarz et al., 2005).

### 4.4. Concluding remarks

Modification of plant compactness due to the MC and plant density treatments showed an effect on cotton yield and quality. In general, applying MC decreases cotton height and the length of fruit branches, resulting in compact plant architecture suitable for mechanical harvesting. For example, applying MC from seedling to boll stages could decrease final length of fruit branches 20% compare with no MC application (Ren et al., unpublished data).

Low plant density causes undesirable branching resulting in excessive removal of bark by mechanical strippers and serious operating problems in the field (Harris et al., 1999). MC application is one of the most important technologies that made the application of UNR (ultra-narrow-row) cotton production possible (Larson and English, 1997), higher plant densities could be used, which has a positive effect on yield (Dowling, 1996). Current harvesting machines either cause harvest losses or have higher levels of waste plant material (Faulkner et al., 2011), and prefer a reduced plant height at high plant density (Oz et al., 2011) compared to relative high plant height and low density in Yellow River region in China. This could be achieved by using plant growth regulators such as MC (Nichols et al., 2003). Extrapolating the findings in this study, applying MC at squaring or at both squaring and flowering stages could perhaps improve cotton fiber and seed quality with increase of yield if plant densities are very high (higher than the maximum density tested here).

As shown in Fig. 8, positive and negative effects of MC and plant density occur simultaneously. To explore the effects of scenarios combining different MC and plant density on plant architecture and hence on cotton yield and quality, a modeling tool such as functional-structural plant modeling (FSPM) could be applied (Vos et al., 2010; Evers et al., 2011). Moreover, optimized plant architecture, e.g. limited plant height, compact canopy size and early maturity, could be adapted to the requirements for mechanical harvesting of cotton.

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