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CROPS AND SOILS RESEARCH PAPER

Cotton radiation use efficiency response to plant growth regulators

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SUMMARY

Plant growth regulators are widely used in cotton production to improve crop management. Previous research has demonstrated changes in crop growth, dry matter (DM) partitioning and lint yield of cotton after the application of plant growth regulators. However, no reports are available demonstrating the effect of plant growth regulators on light interception and radiation use efficiency (RUE). Field studies were conducted in Fayetteville, Arkansas, USA in 2006 and 2007. RUE was estimated for the period between the pinhead square stage (PHS) of growth and 3 weeks after first flower (FF + 3) from plots receiving three applications of the nitrophenolate and mepiquat chloride with *Bacillus cereus* plant growth regulators (Chaperone™) at 7·19 g a.i./ha and Pix Plus® at 41·94 g a.i./ha compared with an untreated control. No differences between the Chaperone treatment and the untreated control were found in the present study. However, Pix Plus significantly reduced plant height (both 2006 and 2007) and leaf area (2007 only), and altered the canopy structure of the crop as recorded by increased values of canopy extinction coefficient. Although DM accumulation was found not to be affected by plant growth regulator treatments, RUE was significantly increased after Pix Plus application, by 33·2%. RUE was increased because less light was intercepted by the Pix Plus treatment for the same biomass production, and this is probably a result of changes in photosynthetic capacity of the leaves and changes in light distribution throughout the canopy.

INTRODUCTION

Solar radiation intercepted by the canopy is the energy input utilized by the crop for production of dry matter (DM). The amount of DM produced by a crop can be calculated when the total amount of radiation intercepted by the canopy and the effectiveness of the crop to utilize the intercepted radiation are known. An analogue of Beer's law can be used to estimate the fraction of incoming radiation intercepted (f) by the canopy (Monsi & Saeki 1953):

$$f = 1 - e^{-k\,\mathrm{LAI}} \qquad (1)$$

where k is the canopy extinction coefficient and LAI is the leaf area index. The extinction coefficient k depends on the leaf angle distribution in the canopy and the angle of radiation (zenith solar angle), and has been reported to be specific to crop type and stage of development (Goudriaan 1988).

The effectiveness of a crop to convert the light intercepted to DM is termed radiation use efficiency (RUE) and is defined as the amount of DM produced (g) per unit of radiation (MJ) intercepted by the crop canopy. The relationship between DM and intercepted radiation has been described by Monteith (1977) as linear. Reported average values of RUE, range from 2·0 to 3·0 and 3·0 to 4·0 g/MJ of absorbed photosynthetically active radiation (PAR) for C_3 and C_4 plants, respectively (Gallagher & Biscoe 1978; Kiniry *et al.* 1989). For cotton (*Gossypium hirsutum* L.), estimated values of RUE for the cultivars Siokra 1–4 (okra leaf) and Deltapine 90 (normal leaf) ranged from 1·70 to 1·92 g/MJ of intercepted PAR across two experiments in Australia (Sadras & Wilson 1997). However, Rosenthal & Gerik (1991) reported RUE values for the cotton cultivars Acala SJ-2, Deltapine 50 and Tamcot CD3H in Texas of 1·46, 1·60 and 1·31 g/MJ of intercepted PAR, respectively. In a CO_2-enriched environment, RUE of cotton increased from 1·56 g/MJ at 370 mg/kg CO_2 to 1·97 g/MJ of intercepted PAR at 550 mg/kg CO_2 (Pinter *et al.* 1994). Furthermore, Sadras (1996) reported values of RUE ranging from 1·18 to 1·71 g/MJ of intercepted PAR for the cultivars CS7S, Siokra S324 and Siokra V-15. Sadras (1996) also

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presented average seasonal values of the canopy extinction coefficient *k* varying between 0·51 and 1·14. For the cultivar Sicala V-2i, across three experiments including nitrogen treatments, RUE was estimated from 0·89 to 3·10 g/MJ of intercepted PAR, with *k* ranging from 0·51 to 0·99 (Milroy & Bange 2003). In other studies, the coefficient *k* was calculated as 0·64 (Stanhill 1976) and *c*. 0·60 until 120 days after sowing (DAS), with an increase thereafter (Milroy *et al*. 2001).

The application of plant growth regulators is a common and widely used practice in cotton production for controlling plant growth, increasing yield and improving management efficiency. The plant growth regulators used in cotton production generally have an effect on crop growth, both vegetative and reproductive, and DM partitioning. However, there have been no reports of effects of plant growth regulators on RUE. It is logical to assume that any chemical that affects canopy dynamics by changing light interception or photosynthetic efficiency will alter RUE.

Mepiquat chloride (1,1-dimethylpiperidinium) is the most widely used plant growth regulator in cotton for control of excessive vegetative growth by inhibiting gibberellin biosynthesis. Previously reported research indicated that mepiquat chloride caused height reduction, earlier maturity and a small yield advantage (Oosterhuis *et al*. 1991). Reduced leaf expansion and shorter main stem and branch internodes, and therefore more compact plants, have been reported after the application of mepiquat chloride (Walter *et al*. 1980; Reddy *et al*. 1990). Advantages of mepiquat chloride applications include yield enhancement, improved lint quality, earlier maturity, increased early boll retention, decreased boll rot and improved light penetration (Gausman *et al*. 1978; Stuart *et al*. 1984; Kerby 1985; Hake *et al*. 1991). The application of mepiquat chloride changes leaf colouration to a darker green (Gausman *et al*. 1978) and increases leaf thickness (Reddy *et al*. 1990; Zhao & Oosterhuis 2000). The product Pix Plus contains mepiquat plus $10{\cdot}5\times10^9$ colony units/l of *Bacillus cereus*.

Another plant growth regulator that has become increasingly important in cotton production in the USA is Chaperone™, which consists of sodium 5-nitroguaiacolate, sodium o-nitrophenolate and sodium p-nitrophenolate. In plants, the phenolic compounds play a central role in metabolism and growth, and are known to increase photosynthetic electron transport, improve and protect membrane integrity, increase enzyme/protein production, increase fruit retention and act as a part of lignin biosynthesis (Robinson 1980). In some cases, lint yields have been reported to increase by 8% after foliar applications of Chaperone (Lackey *et al*. 2004; Oosterhuis & Brown 2005). In addition, increased nitrate–nitrogen, total soluble proteins and Bt endotoxin levels in response to Chaperone have been documented in transgenic cotton cultivars (Oosterhuis & Brown 2005).

Considering the response of the cotton crop to plant growth regulators, it was hypothesized that cotton RUE will be affected by the application of plant growth regulators due to changes in crop growth and canopy dynamics. The objective of the present study was to determine the effect of mepiquat chloride and nitrophenolates on RUE of cotton.

MATERIALS AND METHODS

The effect of plant growth regulators on the RUE of cotton was studied in 2006 and 2007 at Fayetteville, AR (University of Arkansas Agricultural Research and Extension Center) (36°4′N, 94°9′W; 410 m a.s.l.) (Captina silt loam, Typical Fragiudult). The cotton cultivar DP444BGRR (Delta and Pine Land Company, Scott, MS) was planted on 20 May 2006 and 17 May 2007 at a population density of 10 plants/m^2. The fertilization programme was determined according to pre-season soil tests and recommended rates. Weed and insect control were performed according to state recommendations and furrow irrigation was applied according to the Arkansas irrigation scheduler programme (Tables 1 and 2), which is based on soil moisture balance and evapotranspiration (Cahoon *et al*. 1990). The experimental plot size was four rows 10 m long, with 1 m between rows. Treatments consisted of: (i) an untreated control, (ii) Mepiquat with *B. cereus* (as Pix Plus® at 363 ml/ha; BASF Corporation, Research Triangle Park, NC, USA; hereafter referred to as mepiquat) and (iii) mixed nitrophenplates (as Chaperone™ at 582 ml/ha; Asahi Chemical Manufacturing Co., Ltd, Osaka, Japan; hereafter referred to as nitrophenolate) and were arranged in a randomized complete block design with five replications. Plant growth regulators were applied at the pinhead square stage (PHS) of growth, 10 days later (PHS + 10) and at the beginning of flowering (FF) with a CO_2 backpack sprayer calibrated to deliver 94 litres/ha.

RUE was determined for the period between the PHS and 3 weeks after first flower (FF + 3), by the slope

Table 1. *Crop management details for 2006*

Date	Class of compound	Crop procedures undertaken and common names of chemicals used	Active ingredient (a.i.)	Concentration
15 May	Fertilizer	0–0–60	K_2O	560 kg/ha
20 May	Herbicide	Trifluralin	Trifluralin	0·5 litre/ha
20 May		Planted		10 plants/m^2
20 May	Herbicide	Flomet 80DF	Fluometuron	1·12 kg/ha
20 May	Insecticide	AMMO	Cypermethrin	111·7 ml/ha
10 Jun	Insecticide	Bidrin8EC	Dicrotophos	191·6 ml/ha
10 Jun	Fertilizer	46–0–0	N	430 kg/ha
	Urease inhibitor	Agrotain	N-(n-butyl) thiophosphoric triamide (NBPT)	6·8 kg/tn
10 Jun	Herbicide	Roundup–	Glyphosate	0·96 litre/ha
14 Jun		Irrigated		380 m^3/ha
20 Jun	Herbicide	Cotoran	Flumeturon	0·37 kg/ha
20 Jun	Herbicide	MSMA	Monosodium and methanearsonate	37·2 kg/ha
22 Jun		Irrigated		380 m^3/ha
28 Jun	Fertilizer	46–0–0	N	430 kg N/ha
	Urease inhibitor	Agrotain	NBPT	6·8 kg/tn
30 Jun		Irrigated		
5 Jul	Insecticide	Trimaxpro4·44	Imidacloprid	53·5 ml/ha
5 Jul	Plant growth regulator	Mepiquat	Mepiquat chloride	36·8 ml/ha
23 Jul	Insecticide	Bidrin 8EC	Dicrotophos	479 ml/ha
23 Jul	Insecticide	Diamond 0·83EC	Novaluron	61·1 ml/ha
23 Jul	Surfactant	Amigo	Vegetable oil	657·1 ml/ha
25 Jul		Irrigated		380 m^3/ha
7 Aug		Irrigated		380 m^3/ha
15 Aug	Insecticide	Tracer4F	Spinosad	83·9 ml/ha
15 Aug	Plant growth regulator	Mepiquat	Mepiquat chloride	52·13 ml/ha
17 Aug	Insecticide	Tracer4F	Spinosad	87·3 ml/ha
20 Aug	Plant growth regulator	DroppSC	Thidiazuron	62·8 ml/ha
20 Aug	Plant growth regulator	Bollbuster	Ethephon	348 ml/ha
28 Aug	Plant growth regulator	Dropp	Thidiazuron	59·9 ml/ha
28 Aug	Plant growth regulator	DEF 6	S,S,S-tributyl phosphorotrithioate	206 ml/ha
28 Aug	Plant growth regulator	Firstpick	Ethephon	682 ml/ha
			urea sulphate	2182 ml/ha

Spraying equipment was calibrated to deliver at a rate of 93·5 litres/ha.

of the increase in DM over the accumulated intercepted radiation, when DM data were plotted against intercepted radiation from all plots of each treatment. DM was determined every 10–15 days by collecting plant samples from 1 m^2 ground area and oven dried at 55 °C for 48 h. Leaf area of the plant samples was measured using an LI-3100 Area Meter (Li-Cor, Lincoln, NE). Intercepted radiation was calculated by multiplying the incident radiation, measured by a WatchDog 2475 weather station (Spectrum Technologies Inc., Plainfield, IL) located at the edge of the field, with the fraction of intercepted radiation. The fraction of light intercepted by the crop canopy was estimated weekly, starting at PHS, by measuring PAR above and below the canopy in unobstructed sunlight, close to solar noon, using an LI-191S line quantum-source quantum sensor (Li-Cor, Lincoln, NE). For each experimental plot, measurements of fractional light interception were plotted against days after PHS (day zero) and a regression line was fitted (Fig. 1). The quadratic equation developed for each plot was used to estimate fractional light interception for each day of the measuring period. The canopy extinction coefficient was calculated from Eqn (1), solving for k.

Statistical analysis was performed with the JMP 6 software (SAS Institute Inc., Cary, NC). Means were separated with Student's t test ($P \leqslant 0·05$). Statistical differences were evaluated between each plant growth regulator treatment and the untreated control and not between plant growth regulators. Regression analysis

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Table 2. *Crop management details for 2007*

Date	Class of compound	Crop procedures undertaken and common names of chemicals used	Active ingredient (a.i.)	Concentration
21 Mar	Fertilizer	0–0–60	K_2O	627·2 kg/ha
17 May	Herbicide	Trifluralin	Trifluralin	0·5 litre/ha
17 May		Planted		10 plants/m^2
1 Jun	Fertilizer	Liquid urea	N	392 kg N/ha
5 Jun	Herbicide	Roundup	Glyphosate	658·6 litres/ha
5 Jun	Herbicide	Dual	S-metolachlore	0·96 litre/ha
10 Jun		Irrigated		380 m^3/ha
19 Jun	Herbicide	Roundup	Glyphosate	0·96 litre/ha
19 Jun		Irrigated		380 m^3/ha
24 Jun	Insecticide	Centric	Thiamethoxam	31·05 ml/ha
25 Jun	Fertilizer	Liquid urea	N	392 kg N/ha
11 Jul		Irrigated		380 m^3/ha
17 Jul	Herbicide	Valor	Flumioxazin	74·5 ml/ha
17 Jul		Irrigated		380 m^3/ha
22 Jul	Insecticide	Acephate 90WSP	Acephate	0·6 kg/ha
31 Jul	Insecticide	Acephate 90WSP	Acephate	0·6 kg/ha
31 Jul	Insecticide	Tombstone	Cyfluthrine	36·5 ml/ha
31 Jul	Insecticide	Tracer 4F	Spinosad	87·1 ml/ha
5 Aug	Plant growth regulator	DroppSC	Thidiazuron	62·8 ml/ha
5 Aug	Plant growth regulator	Bollbuster	Ethephon	347·9 ml/ha
18 Aug	Plant growth regulator	Dropp	Thidiazuron	59·9 ml/ha
18 Aug	Plant growth regulator	DEF 6	S,S,S-tributyl phosphorotrithioate	206 ml/ha
18 Aug	Plant growth regulator	Firstpick	Ethephon	682 ml/ha
			urea sulphate	2182 ml/ha

Spraying equipment was calibrated to deliver at a rate of 93·5 litres/ha.

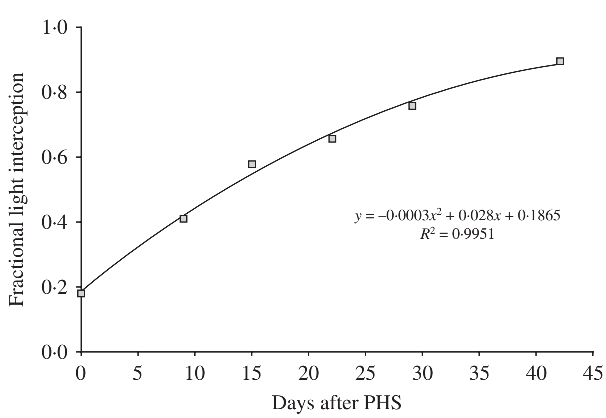

Fig. 1. An example of calculating daily fractional light interception. For each experimental plot, measurements of fractional light interception were plotted against days after PHS (day zero) and a regression line was fitted, as shown above. The quadratic equation developed for each plot was used to estimate fractional light interception for each day of the measuring period.

was used to test differences in productivity of DM and RUE between each plant growth regulator treatment and the untreated control. Differences across years were tested using stepwise linear regression analysis.

RESULTS

The crop reached PHS at 44 DAS in 2006 and 49 DAS in 2007, with the beginning of flowering at 65 and 71 DAS for 2006 and 2007, respectively. Foliar application of nitrophenolate did not significantly affect plant height or leaf area index (LAI) in either year of the study (Table 3). In contrast, mepiquat applications significantly decreased plant height in 2006 ($P = 0{\cdot}020$) and 2007 ($P = 0{\cdot}003$). LAI was close to being significantly decreased by mepiquat application in 2006 ($P = 0{\cdot}059$) and was significantly decreased in 2007 ($P = 0{\cdot}034$). While no differences were observed for the nitrophenolate treatment, mepiquat application also affected the crop canopy structure, with higher values of canopy extinction coefficient recorded in 2006 ($P = 0{\cdot}005$) and 2007 ($P = 0{\cdot}003$) (Fig. 2).

Accumulation of DM, for the duration of the study, did not differ between the untreated control and the two plant growth regulator treatments in either year (Table 4). However, the partitioning of DM was altered by the mepiquat treatment in 2007, with the fraction of total DM partitioned to stems being significantly decreased ($P = 0{\cdot}007$) and to fruit significantly increased

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Table 3. *Plant height and LAI measured at FF+3*

	Plant height (m)				LAI			
Treatment	2006		2007		2006		2007	
Untreated	0·96		1·32		2·807		3·862	
Nitrophenolate	0·93	(ns)*	1·30	(ns)	2·987	(ns)	3·939	(ns)
Mepiquat	0·87	(P<0·05)	1·05	(P<0·01)	2·562	(ns)	3·189	(P<0·05)

* Comparison of each plant growth regulator treatment with the untreated control. ns = not significant.

Table 4. *DM production and intercepted PAR for the period between the pinhead square of growth and FF+3*

	DM production ($g/m^2/day$)				Intercepted PAR (MJ/m^2)			
Treatment	2006		2007		2006		2007	
Untreated	13·6		14·7		201		233	
Nitrophenolate	14·8	(ns)*	13·5	(ns)	214	(ns)	227	(ns)
Mepiquat	14·7	(ns)	13·7	(ns)	196	(ns)	218	(P<0·01)

* Comparison of each plant growth regulator treatment with the untreated control. ns = not significant.

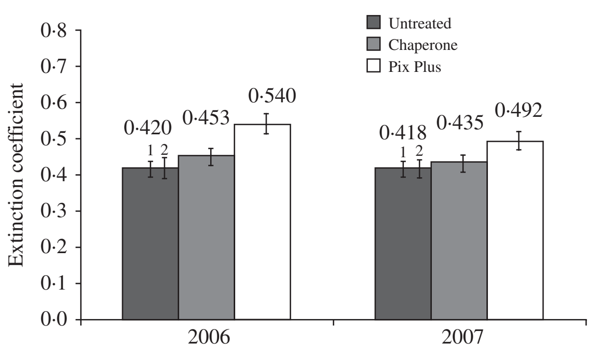

Fig. 2. Canopy extinction coefficient (k) values for 2006 and 2007, estimated at the FF stage of growth. ±1 S.E.D. bars are shown for treatment comparison (1, untreated control to chaperone; 2, untreated control to mepiquat chloride).

(P=0·022) compared with the untreated control (Fig. 3).

The amount of intercepted radiation by the crop canopy, for the duration of the study, was not significantly affected in 2006 by either nitrophenolate (P=0·169) or mepiquat (P=0·073) treatment compared with the untreated control (Table 4). Similarly, in 2007, nitrophenolate applications did not alter (P=0·282) the amount of intercepted radiation by the cotton crop (Table 4), but mepiquat significantly (P<0·01) lowered the amount of radiation intercepted (Table 4).

Differences in total intercepted radiation can be explained by differences in the fractional light interception of the crop for the PHS, FF and FF+3 (Fig. 4). Higher fractional light interception (P=0·010) was observed in 2006 for the nitrophenolate treatment compared with the untreated control at FF+3, while the mepiquat treatment significantly decreased fractional light interception (P=0·008) at the FF stage. However, the increase in fractional light interception of the nitrophenolate treatment did not lead to an increase in the intercepted radiation, possibly due to the small degree of the increase (6·6%) and the small amount of time available for accumulation of radiation. In 2007, a significantly lower (P=0·004) fraction of incident radiation was intercepted by the mepiquat treatment at FF+3.

Regression analysis revealed no significant differences between the untreated control and the nitrophenolate treatment in RUE for either 2006 (P=0·224) or 2007 (P=0·730) (Table 5). However, for mepiquat application, the analysis was run separately for each year and RUE was significantly increased (P<0·05) in 2006 only when compared with the control treatment (Table 5). Statistical analysis performed across the 2 years of the study provided mean values with RUE at 2·26 g/MJ of intercepted PAR for the untreated control, 2.50 g/MJ PAR for the nitrophenolate treatment, and 2·97 g/MJ PAR for the mepiquat treatment, with the effect of mepiquat applications being statistically significant (P=0·021). Reporting mean values of RUE across the 2 years of the study is possible due to lack of a significant treatment × year interaction

Table 5. *Effect of plant growth regulator treatments on RUE of cotton*

Treatment	RUE (g/MJ)		
	2006	2007	Across years
Untreated	2·4	2·4	2·2
Nitrophenolate	2·7 (ns)*	2·6 (ns)	2·5 (ns)
Mepiquat	3·2 ($P<0·05$)	3·2 (ns)	3·0 ($P<0·05$)

* Comparison of each plant growth regulator treatment with the untreated control. ns = not significant.

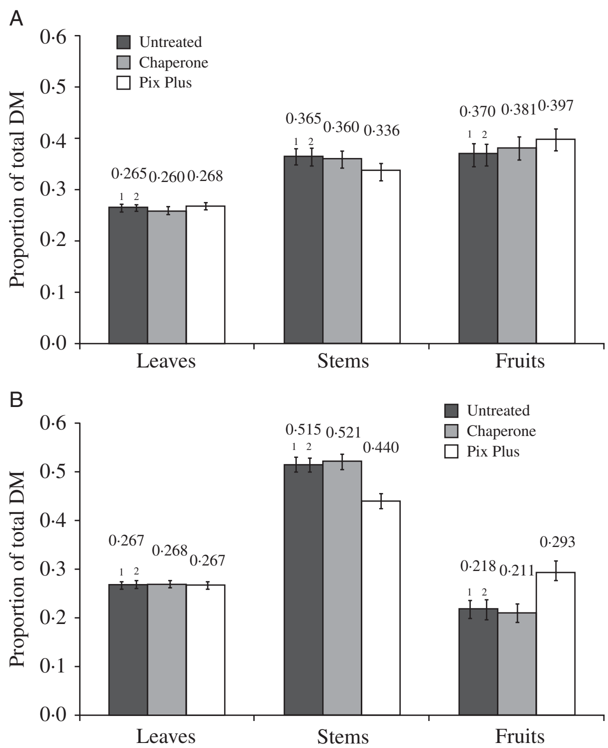

Fig. 3. DM partitioning between leaves, stems and fruit measured at FF+3 for 2006 (*a*) and 2007 (*b*). ±1 S.E.D. bars are shown for treatment comparison (1, untreated control to chaperone; 2, untreated control to mepiquat chloride).

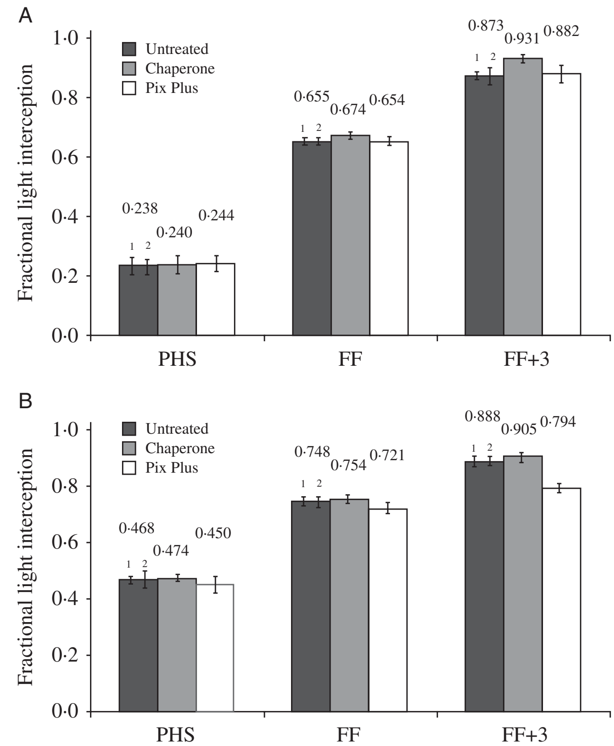

Fig. 4. Fractional light interception measured at PHS, FF and FF+3 in 2006 (*a*) and 2007 (*b*). ±1 S.E.D. bars are shown for treatment comparison (1, untreated control to chaperone; 2, untreated control to Pix Plus).

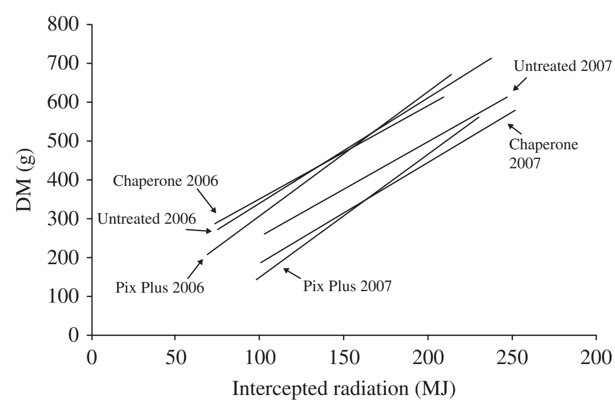

Fig. 5. Slopes of the increase in DM over the accumulated intercepted radiation (RUE) of the untreated control, nitrophenolate and mepiquat treatments for 2006 and 2007.

(Fig. 5). In addition, the mean square error for both years was very similar therefore allowing the analysis to be combined across years, which provides a better indication of the overall effect of a treatment when there is no treatment × year interaction.

DISCUSSION

In the present study, the effect of the plant growth regulators nitrophenolate and mepiquat on the growth and RUE of cotton was evaluated. None of the parameters recorded appeared to be significantly affected by multiple foliar applications of nitrophenolate, except for an increase in fractional light interception at FF+3 in 2006 only. In contrast, the application of mepiquat (a.i.: mepiquat chloride) altered the crop canopy structure and the efficiency of the crop in converting intercepted radiation to DM. LAI of the crop was decreased by mepiquat chloride, as previously

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described by Reddy *et al.* (1990). A quantitative estimate of the canopy structure is the canopy extinction coefficient, with higher values estimated in this study following mepiquat chloride applications.

DM partitioning of the cotton crop changed in favour of fruiting organs; this was similar to previous reports of increased partitioning to fruits after applications of mepiquat chloride (Walter *et al.* 1980; Zhao & Oosterhuis 2000).

RUE values presented in the present paper are in most cases higher than values reported in previous research for cotton, where RUE is measured for the whole season (Rosenthal & Gerik 1991; Pinter *et al.* 1994; Sadras 1996; Sadras & Wilson 1997). However, Milroy & Bange (2003) reported values as high as 3·10 g/MJ of intercepted PAR for RUE measured for only part of the season, similar to the values estimated in the present study.

Treatment with mepiquat chloride increased RUE of the cotton crop, the cause of which could be associated with previously reported increased single-leaf photosynthesis (Zhao & Oosterhuis 2000) and whole canopy CO_2 exchange rates (Hodges *et al.* 1991) following application. Furthermore, the application of mepiquat chloride altered the canopy of the crop, with the treated cotton plants being more compact, usually associated with delayed canopy closure. Previous research demonstrated a decrease in the proportion of light intercepted by the upper leaves, with an increase in light penetration to the middle portion of the canopy after the application of mepiquat chloride (Gwathmey *et al.* 1995). It is therefore hypothesized that a larger portion of the canopy, both on the top and at the sides of the mepiquat chloride-treated plants would be exposed to more direct radiation. The higher RUE values reported in the present study may be attributed to light interception differences, as well as to improved carbon assimilation rates due to the application of mepiquat chloride.

Another point of interest is the higher values of canopy extinction coefficient in conjunction with the increased RUE of mepiquat chloride-treated plants in the present study. The higher canopy extinction coefficient may not be the reason for the higher RUE: Milroy & Bange (2003) found that k had little impact on the RUE of cotton. In contrast, Sadras (1996) previously reported that a higher canopy extinction coefficient can lead to lower RUE in cotton. However, this relationship was only demonstrated for the so-called 'favourable' conditions of low plant density (5 plants/m^2) and high nitrogen (180 kg N/ha), with no relationship found for less favourable conditions (plant density of 12·5 plants/m^2 and no fertilizer).

The results show that the effect of mepiquat chloride measured at the leaf level translates to canopy level differences. In addition, it supports the notion that mepiquat chloride affects yield via effects on growth as well as partitioning of DM. To the authors' knowledge, this is the first report of a commercially used plant growth regulator affecting the RUE of any crop.

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