THE USE OF PLANT GROWTH REGULATORS AND OTHER ADDITIVES IN COTTON PRODUCTION

Derrick Oosterhuis and William C. Robertson[1]

INTRODUCTION

The cotton plant is a perennial with an indeterminate growth habit, and reputed to have the most complex growth habit of all major row crops. Furthermore, it is very responsive to management and changes in the environments and responds to any perturbations in its environment with a dynamic growth response that is often unpredictable. Cotton producers and researchers have, therefore, used plant growth regulators (PGRs) and other cultural practices as a means to manage the balance between vegetative and reproductive growth for efficient cotton production. The following provides some information on why we use PGRs, the problem with many of the existing PGRs, and a summary of field and growthroom research on the evaluation PGRs at the University of Arkansas. Starter and foliar fertilizers will not be dealt with here.

WHY USE PGRS?

Chemical PGRs have been widely used in cotton production in an attempt to adjust plant growth and to improve lint yield and fiber quality. Obviously, the best means to achieve these aims is through the use of desirable genetics in the form of well-adapted high-yielding varieties. However, due to the very varied environment (e.g., soil, temperature, insects, and rainfall) in which cotton is grown, it is almost impossible to have a perfectly adapted variety capable of providing high yields in all circumstances. Therefore, PGRs and other stress management practices have been used in an attempt to consistently achieve high yields.

WHAT IS A PGR?

PGRs encompass a broad category of compounds that promote, inhibit, or otherwise modify plant physiological or morphological processes. Some PGRs are plant hormones or their analogues; others are simply metabolic regulators. PGRs are classified as organic compounds that alter the growth and development of plants. Unlike plant hormones that are endogenously produced by the plant, PGRs may be considered chemical compounds either produced naturally by the plant or synthetically by a chemist. PGRs are biologically active at very low concentrations and elicit responses similar to those observed from plant hormones. Since most plant growth and development

[1] Distinguished Professor, Department Crop, Soil and Environmental Sciences, University of Arkansas, Fayetteville; Cotton Extension Specialist, Cooperative Extension Service, University of Arkansas, Little Rock.

processes are regulated by natural plant hormones, these processes may be manipulated by either (1) altering the plant hormone level, or (2) changing the capacity of the plant to respond to its natural hormones. In recent years, synthetic PGRs have been investigated for their ability to alter cotton growth and development in an attempt to control growth and improve productivity. PGRs should be considered as management tools in the producer's arsenal that can be used to ensure efficient production. These compounds are diverse in both their chemistry and use. A comprehensive review of the use of PGRs in cotton production has been presented by Cothren and Oosterhuis (2000).

THE PROBLEM!

In the past two decades, many new PGR compounds have been developed or "accidentally" discovered and subsequently tested on cotton with variable and sometimes disappointing results due to a variety of reasons, including poor chemical compounds, changing environments, and varied production practices. Producers are bombarded with a barrage of PGRs and incredible claims about their benefits. Usually there are no creditable data to support these claims on which producers can base their decisions about using these PGRs.

Producers would be wise to keep an eye open for unsubstantiated claims about PGRs and, at the same time, develop a thick skin against all the wonderful claims made for these products. When a question arises about whether to use a new or existing PGR, research results from an accredited institution should be requested and evaluated. The main points to look for are: Does the PGR do what it is supposed to? Does it perform consistently from one year to another? Is it economical? The basic problem is that plant responses to PGRs are complicated by the interaction of environment and cultural practices. Therefore, for a PGR to be widely accepted, it must perform consistently in a given production scheme.

EVALUATION OF PGRs

PGRs have been evaluated at the University of Arkansas for the past two decades (e.g., Urwiler *et al.*, 1987; Oosterhuis and Janes, 1994). The overall aim of the PGR program at the University of Arkansas is to improve our understanding in order to control plant growth and enhance yield. This necessitates field studies with normal cotton production practices, as well as growthroom evaluation for mechanistic studies. Recent research has focused on the physiological effects and underlying mechanisms of PGRs (e.g., Guo *et al.*, 1994; Oosterhuis, 1996; Zhao and Oosterhuis, 1997a, 1997b) in an effort to adapt their use to the growth requirement of specific crops and environments. Specific objectives of the research program, depending on the compound concerned, are:

- Compare commercially available PGRs in field tests for effect on growth and yield.
- Determine the optimum application rate and timing for the more promising PGRs.
- Investigate the effect of PGRs on emergence, root growth, and seedling development.

- Determine the mode of action of the more promising PGRs.

The information from these studies is used to adapt the technology to best fit into current cotton production systems, and to provide information for farmers to select and use PGRs.

PGRs STUDIED

PGRs encompass a broad category of compounds that promote, inhibit, or otherwise modify plant physiological or morphological processes. In the past two decades, many PGR compounds have been developed and tested on cotton. However, the majority of them have not proven satisfactory for one reason or another and have either been discarded or are not used very much. The PGRs that have been used and tested in cotton production in the mid-South in recent years (Table 1) include Atonik, cycocel, Crop+2, Cytokin, Early Harvest, Maxon, PGR-IV, mepiquat chloride, Pix Plus, and PHCA. There are also numerous other so-called PGR compounds that have not been listed because they did not prove to be effective in preliminary testing, they were withdrawn by their manufacturers, or we were unable to get test samples from the companies concerned.

It is important to know and understand for what purpose a particular PGR was designed. For example, a distinction is usually made between growth retardants (e.g., mepiquat chloride, Pix Plus, and cycocel) and growth or yield enhancers (e.g., PGR-IV and Cytokin). However, a growth retardant such as mepiquat chloride, by the nature of its effect on plant growth, may often also elicit other positive growth features such as earlier maturity and a yield enhancement. Zhao and Oosterhuis (2000a) have demonstrated that the main advantage of Pix Plus over mepiquat chloride may lie in the improved partitioning of dry matter by Pix Plus into fruiting structures.

PGRs AND YIELD

A routine field test comparing commercially available PGRs has been conducted for over 20 years at University of Arkansas experiment stations in the Mississippi Delta. The rates and timings of the PGRs tested were according to best-scenario recommendations from either the chemical companies concerned or University research findings. The PGRs tested in the 1990s include Atonik, Cycocel (CCC), Maxon, Early Harvest, PGR-IV, PHCA, Cytokin, Crop+2, Mepiquat Chloride (Pix™), and Pix Plus (formerly MepPlus). Foliar spray treatment applications were made with a CO_2 backpack sprayer calibrated to supply 10 gal/acre of solution. Fertilizer, weed control, and insect measures were added according to Cooperative Extension Service recommendations. The experiments were furrow-irrigated as needed throughout the growing season. Routine records were made of plant height and main-stem node number, petiole nutrient concentration, maturity, boll weight, boll number, lint percentage, fiber quality, and yield.

The yield response with added PGRs has been variable and inconsistent (Table 2). There were no significant treatment effects on yield during the past 3 years, possibly due to the unusually stressful seasons masking any possible PGR effects. Part of the reason for variable yield responses from PGRs is the extremely varied environments and crop conditions under which the PGRs are used, and also the lack of understanding of the nature and performance of the specific chemical compounds. Another obvious reason is that some of these chemicals do not really do the job they are supposed to!

The most consistent response has been shown with PGR-IV (a significant yield increase 43% of the time), compared to PHCA (40%), Cytokin (33%), Pix (29%), and Crop+2 (20%). Early Harvest has not shown any significant effect on yield in the 3 years it has been tested. The average yield increase over the past 7 years from PGR-IV was 46 lb lint/acre, and from Pix was 20 lb lint/acre. However, Pix is a growth retardant and as such was not conceived as a yield enhancer. Pix studies in Arkansas have shown significant yield increases from Pix about 25% of the time associated with the controlled plant growth (Oosterhuis *et al.*, 1991). The effect of PGRs on boll weight and boll numbers has shown no clear trend.

Another way to use these data is to consider the percentage increase for each PGR compared to the untreated control. For example, the average response to mepiquat chloride was 2.7% (or 13 lb lint per bale of yield), for PGR-IV it was 4.0%, and for Early Harvest it was 2.0% (or 13 lb lint per bale of yield).

OTHER GROWTH EFFECTS OF PGRs

Plant height was significantly and consistently decreased by mepiquat chloride and Pix Plus by 15-20%, sometimes with a slight accompanying decrease in main-stem node number. Cycocel decreased height significantly but not as much as Pix; however, cycocel (which is still used on cotton in many developing countries) significantly decreased yield in other related studies. Most other PGRs had either no effect on plant height and node number or a small increase in height due to the growth-promoting properties of the compound. In general, PGRs increased the concentration of certain nutrients in the petiole, but as with yield, the results have been inconsistent. There have been no significant effects of the PGRs tested on fiber quality.

SEED TREATMENT AND IN-FURROW APPLICATIONS OF CHEMICAL ADDITIVES

Cotton is often planted in the mid-South under unfavorable planting conditions (e.g., cool, wet soils). Therefore, producers have been interested in PGRs or fertilizer additives for enhancement of seedling growth as well as increased yield. Earlier growthroom studies showed enhanced root growth and seedling vigor from using in-furrow seed treatment with PGR-IV (Oosterhuis and Zhao, 1995) and with ASSET (Steger *et al.*, 1998). However, field studies have been less than conclusive, often with variable results (Robertson, 1998). Ongoing field studies continue to evaluate chemicals added at planting to enhance seedling growth and increase yield (e.g., Oosterhuis and Coker, 2000).

EFFECT OF PGRs ON ROOT GROWTH

Poor root growth early in the season in Arkansas, as a result of cool, wet soils has been a serious limitation to optimum yields. PGRs, in addition to fungicides and insecticides, may offer an opportunity for enhancing early-season plant development. Our research has shown that in-furrow or seed treatment with certain PGRs is beneficial to early root growth and seedling development in cotton. For example, growthroom studies revealed that the in-furrow applications of PGR-IV resulted in dramatic increases in root length, root dry weight, number of lateral roots per plant, and nutrient uptake 1 week after planting (Oosterhuis and Zhao, 1995). These differences were still apparent 5 weeks later at pinhead square but to a lesser degree. A range of PGR substances have been evaluated in growth chamber studies for their effect on root growth and seedling development. A number of compounds such as PGR-IV and ASSET applied in-furrow or as a seed treatment have shown promise for enhancement of root growth and early shoot development, although field results have not always been consistent. We have also shown that indole butyric acid (IBA) and Pix plus IBA stimulated root growth, but Pix alone did not stimulate root (Urwiler and Oosterhuis, 1986).

RATE AND TIMING

The complex growth pattern of cotton and its dynamic response to management and environment necessitates precise application timing and rate of foliar-applied PGRs for maximum control of plant growth for optimum yield response. Generally, the company that manufacturers the PGR provides the recommended rates and timing for its compounds, but in many cases University of Arkansas scientists use field and growthroom tests to determine or confirm these rates for the more promising compounds. We have evaluated only PGR-IV, Early Harvest, Atonik, and mepiquat chloride for rate and timing, while the rates and timing of the other PGRs have been recommended by the respective manufacturers. Information concerning rate and timing needs to be continually updated as we learn more about each specific PGR (benefits and mode of action) so as to best adapt the technology to our existing cropping systems.

PHYSIOLOGICAL EFFECTS OF PGRs AND MODE OF ACTION

A second level of research involves studying the more promising PGRs for their effect on the physiology of the cotton plant and their mode of action. Detailed studies have been conducted in Arkansas on mepiquat chloride (Oosterhuis *et al.*, 1991), PGR-IV (Oosterhuis, 1995), and recently on Pix Plus (Zhao and Oosterhuis, 2000a). The effects of selected PGRs on photosynthesis, carbohydrate status, membrane integrity, and nutrient uptake have been documented and the results used to explain the mode of action (Guo *et al.*, 1994). The use of PGRs to enhance nutrient uptake has also been shown (Guo *et al.*, 1994).

Our research has implemented sugar alcohols (polyols) in the action of PGRs (Guo and Oosterhuis, 1995). Pix Plus has been shown to increase the levels of the polyol myo-inisotol, which is believed to be related to the improved partitioning of dry matter into cotton bolls (Zhao and Oosterhuis, 2000b). Phenolic acids play a possible role as modulators of hormonal activity. We recorded the temporal patterns of phenolic acids in cotton fruit in relation to abscission, sensitivity to environmental stress (shade and water stress), ethylene evolution, and abscisic acid concentration of fruits. This research suggested that phenolic acids modify growth and development of cotton fruit during stress, and indicated the potential for use of phenolic acids as growth regulators in cotton (Hampton and Oosterhuis, 1990).

Since leaf carbohydrates represent the primary metabolic carbohydrate pools for cotton plants, an understanding of their dynamics during cotton growth and boll development is essential. Our interest has focused on understanding the dynamics of carbohydrate changes during leaf, canopy, and fruit development (Zhao and Oosterhuis, 2000b), and the possibility of influencing carbohydrate translocation out of the leaf using PGRs. We have used ^{14}carbon-labeling techniques to show the influence of PGRs on translocation. Certain PGRs, e.g., PGR-IV and possibly mepiquat chloride, can enhance translocation of carbohydrates out of the leaf, which was associated with an increase in leaf photosynthesis and a yield advantage. Photosynthesis is often improved when PGRs are used, but this is thought to be an artifact of the improved movement of carbohydrates out of the leaf, allowing photosynthesis to occur at a maximum rate.

Bacillus cereus **(IN PIX PLUS)**

Field and growthroom studies are being conducted to understand the role of *Bacillus cereus,* the new bacterial component of Pix Plus. Information to date implicates *B. cereus* in increased dry matter partitioning to the fruit (Zhao and Oosterhuis, 2000a) through improved efficiency of biochemical pathways in the leaf, possibly from bacterial metabolites on the leaf surface.

EFFECTS OF PGRs ON STRESSED COTTON

Research at the University of Arkansas has shown that PGR-IV can have a remedial effect on stressed cotton. For example, under conditions of mild water deficit, PGR-IV can partially alleviate the detrimental effect of water stress, i.e., on photosynthesis (Zhao and Oosterhuis, 1997b). We have also shown similar advantageous alleviation of stress effects under conditions of mild flooding and canopy shading (Zhao and Oosterhuis, 1997a). PGR-IV has also been reported to help under conditions of low temperature (Tom Cothren, Texas A&M University, personal communication). This remedial action of PGRs may ultimately turn out to be one of their more important roles in cotton production in the future.

PGRs AND EARLY MATURITY

The nature of the action of PGRs, e.g., decreasing vegetative growth, increasing fruit set, and improving partitioning to fruit, often causes earlier maturity of the developing boll load. In our studies, only Pix has shown a consistent trend toward hastening maturity, as indicated by reaching physiological cutout of NAWF=5 about 7 days earlier, with a slightly larger percentage harvest at first pick. There was not a clear trend for any other PGR compared to the control toward early cutout. In general, mepiquat chloride causes a significantly earlier maturity about 50% of the time (Oosterhuis *et al.*, 1991).

COMPATIBILITY OF PGRs

Producers are often tempted to combine agricultural chemicals in the same tank to save on application costs. Questions have arisen about the compatibility of mepiquat chloride and PGR-IV because one is an anti-GA and the other contains GA as a central component. Research has shown that these two PGRs can be safely applied together without any harmful effect on yield, although the reduction in plant height from mepiquat chloride may be slightly decreased (Guo and Oosterhuis, 1994). Although PGR-IV and mepiquat chloride were shown to be compatible, it is recommended to apply them 1 wk apart.

NEW DEVELOPMENTS

The discovery of most commercial PGRs appears to have resulted from serendipitous events, and therefore, the nature and action of the chemicals has been quite varied. It is difficult to predict what new variations of PGR will arise. Current trends in the selection and design of specific PGRs has involved multi-entity PGRs, polyhydroxy carboxylic acids, and the addition of micronutrients. It is obvious that the discovery and acceptance of three new classes of PGRs—namely jasmonates, salicyclic acid, and brassinosteriods—will lead to the development of new commercial PGRs. The use of future PGRs will probably focus more on the fruit development period and on remedial applications, as well as a more coordinated systems approach to management coupled with more precise crop monitoring techniques.

CONCLUSIONS

PGRs allow for manipulation of physiological processes in plant growth and development for more efficient crop management and increased yields. Research at the University of Arkansas has shown that the use of PGRs in cotton is a useful production practice for controlling plant growth and enhancing yield. However, the effect of available PGRs on growth and yield has generally been inconsistent and disappointing. This is partially attributed to seasonal variations in weather and crop conditions, but also to poor PGR materials and a lack of previous testing of the chemicals concerned. In some cases, the chemicals are not suited for use in cotton. Good management decisions are therefore necessary in deciding whether to use a PGR and also in selecting the most appropriate compound. Continued research at both applied and basic levels will elucidate the specific effects and mode of action of PGRs and thereby aid in adapting their use to current cotton production systems while also improving their performance and consistency.

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Table 1. Plant growth regulator common names, chemical makeup, timing, and rates of chemicals field tested.

Treatment	Chemical makeup	Company	Timing	Rate[z]
Atonik	Na salts of ortho-nitrophenol, para-nitrophenol, and 5-nitro-guaiacol	Asahi Chem. Mfg. Co.	PHS[y], FF[x], FF+3 wks	500 ml/A, 600 ml/A, 600ml/A
Crop+2	protein digest extract	Cytozyme Labs Inc.	3-4 leaf, PHS, FF	16 oz/A, 16oz/A,16 oz/A
Cytokin	natural cytokinins	PBT Inc.	PHS, FF, FF+3 wks	4oz/A, 8oz/A, 8oz/A
Early Harvest	IBA, GA, cytokinin	Griffin Corporation	IF[w], PHS, FF	2oz/A,4oz/A,4oz/A
Maxon	IBA, GA	Terra International	IF, PHS, FF	2 oz/A, 2 oz/ A, 4 oz/A
Pix Plus[v]	Mepiquat Chloride and *Bacillus cereus*	BASF (Microflo Company)	PHS, FF	6 oz/A, 8 oz/A
PGR-IV	IBA, GA plus fermentation broth	Microflo Company	IF, PHS, FF	2 oz/A, 4 oz/A, 4 oz/A
PHCA	polyhydroxycarboxycylic acid	Microflo Company	PHS, FF, FF+3 wks	8 oz/A, 16 oz/A, 16 oz/A
Pix	mepiquat chloride	BASF	PHS, FF	6 oz/A, 8 oz/A

[z] According to manufacturer recommendations or previous research.

[y] PHS = pinhead square.

[x] FF = first flower.

[w] IF = in-furrow at planting.

[v] MepPlus was renamed Pix Plus in 1999.

Table 2. Effect of plant growth regulators on lint yield in Arkansas 1993-1999.

PGR	1993	1994	1995	1996	1997	1998	1999	% of control[z]
	lb/acre							%
Control	790	1094	1100	1297	1108	896	1080	---
Atonik	850	1153	1070	1245	----[y]	----	----	+5.5
Cycocel	----	----	----	----	1047	----	----	–5.5
Crop+	941	1124	1064[x]	1339[y]	----	----	----	–0.3
Cytokin	879	1161	1028	1266	1122	----	----	+1.9
Early Harvest	----	----	----	1308	1148	901	1114	+2.0
Maxon	----	----	----	1328	----	----	----	+2.4
PHCA	975	1159	1151	1308	---	---	---	+8.6
Pix Plus[w]	----	----	----	----	1130	922	1087	+1.0
PGR-IV	906	1169	1121	1374	1158	860	1063	+4.0
Mepiquat chloride	960	1129	1027	1389	1076	907	1034	+2.7
Bacillus cereus	----	----	----	----	----	----	1074	–0.6
LSD	73	54	142	69	NS	NS	NS	---

[z] Calculated for individual years and meaned overall.

[y] Not evaluated in that year.

[x] Crop+2 used in 1995 and 1996.

[w] MepPlus was renamed Pix Plus in 1999.