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Physiologic and Yield Responses of Shaded Cotton to the Plant Growth Regulator PGR-IV

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Abstract. The plant growth regulator PGR-IV has been reported to improve the growth, boll retention, and yield of cotton (*Gossypium hirsutum* L.) under optimum growing conditions. However, little is known about the response of cotton to PGR-IV under low light stress. A 3-year field study was conducted to determine if applying PGR-IV before an 8-day period of shade (63% light reduction) benefitted the growth and yield of shaded cotton. Shading during early squaring did not affect yield. Shading after the first flower stage significantly increased leaf chlorophyll concentration and fruit abscission and decreased the leaf photosynthetic rate, nonstructural carbohydrate concentrations, and lint yield. Foliar application of PGR-IV at 292 mL ha^{-1} at early squaring and first flower did not improve the leaf photosynthetic rate of shaded cotton. However, shaded plants receiving PGR-IV had higher nonstructural carbohydrate concentrations in the floral buds and significantly lower fruit abscission than the shaded plants without PGR-IV. Applying PGR-IV to the foliage before shading resulted in a numeric increase (6–18%) in lint yield compared with shaded plants without PGR-IV. The decreased fruit abscission from the application of PGR-IV was associated with improved assimilate translocation. The yield enhancement from foliar application of PGR-IV was attributed to increased fruit retention. However, the average boll weight of shaded plants with PGR-IV tended to be lower than that of shaded plants without PGR-IV. Lint percentage was not affected by PGR-IV. Foliar application of PGR-IV appears beneficial for increasing the fruit retention of shaded cotton.

Key Words. Cotton—Shade—PGR-IV—Nonstructural carbohydrates—Lint yield—Yield components

Light is one of the most important factors affecting leaf photosynthesis, growth, development, and yield of cotton. Dunlap (1943) reported 75% fewer mature bolls associated with low light intensity at the flower stage, with most of the fruit abscission occurring during the 3rd and 4th days of the shading period. Under low light intensity, cotton plants fruit more slowly and with less fruit retention than plants under normal light (Roland 1974). Sorour and Rassoul (1974) reported that a 3-week period of shade (50% light reduction) after first flower decreased the number of flowers and increased boll abscission significantly, although the effects of shading at different growth stages after flowering on fruit abscission, yield, and yield components were similar. Recent research by Pettigrew (1994) suggested that when cotton plants were shaded for 42 days using shade cloth of 30% light reduction, lint yield decreased 20% compared with an unshaded control.

Low light intensity in the cotton canopy may be caused by adverse weather and excessive vegetative growth. Periods of cloudy, overcast weather occur frequently in the Mississippi River Delta, and it is speculated that these cloudy, overcast periods have a detrimental effect on cotton growth and fruit retention. Guinn (1976, 1982) reported that ethylene and abscisic acid (ABA) contents in cotton young bolls increased dramatically under low light conditions and resulted in boll abscission. Hampton (1990) found that shade increased the production of phenolic substances in large squares and flowers of field-grown cotton and was associated with inducing fruit abscission.

PGR-IV is a plant growth regulator (Microflo, Lakeland, FL) containing 27.0 mg of gibberellic acid (GA)/liter, 30.4 mg of indolebutyric acid (IBA)/liter, and a

Abbreviations: ABA, abscisic acid; GA, gibberellic acid; IBA, indolebutyric acid; FF, first flower; PF, peak flower; BD, boll development; PHS, pinhead square; PPFD, photosynthetic photon flux density; DW, dry weight; TNC, total nonstructural carbohydrate; LSD, least significant difference.

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proprietary blend of nonpesticidal inert ingredients. Previous studies have shown that applying PGR-IV can improve cotton root growth, leaf area, photosynthesis, boll retention, and yield under optimum growing conditions (Dillon and Johnson 1992, Hickey 1991, Hickey and Dillon 1993, Oosterhuis 1995, Oosterhuis and Zhao 1993, 1994). Livingston et al. (1992) reported that the percentage of yield increase from the foliar application of PGR-IV to cotton was higher under dry land than under irrigated conditions. Guo and Oosterhuis (1995) showed that PGR-IV could improve the translocation of pinitol out of the leaves of low temperature-stressed soybean [*Glycine max* (L.) Merr.]. Foliar application of PGR-IV before water deficit stress partially alleviated the detrimental effects of water stress on leaf photosynthesis and dry matter accumulation of growth chamber-grown cotton plants (Zhao and Oosterhuis 1997). However, it is not known if PGR-IV is beneficial to shaded cotton plants. These observations led to the hypothesis that PGR-IV may partially alleviate the detrimental effect of shade on cotton fruit abscission by improving sugar movement from leaves to fruits. The objective of this study was to determine if the foliar application of PGR-IV before shade can enhance fruit retention, leaf photosynthesis, and lint yield of shaded cotton.

Materials and Methods

The experiment was conducted at the Arkansas Agricultural Research and Extension Center, University of Arkansas in Fayetteville, 1993 to 1995. Cotton cv. Deltapine 20 was planted on 26 May 1993, 17 May 1994, and 15 May 1995. The plots consisted of five rows spaced 1 meter apart, oriented in a south-north direction, and hand-thinned to nine plants/meter row when the seedlings had three true leaves. Preplant fertilizer was applied at a rate of 45, 30, and 75 kg of N, P, and K ha^{-1}, respectively, and side dressed with 56 kg of N ha^{-1} at the early square stage. All other production practices were standard according to Arkansas cotton production recommendations (Bonner 1993).

Seven different treatments were applied in 1993: (1) control with no shading and no PGR-IV, (2) shading at the first flower (FF) stage without PGR-IV, (3) shading at FF with PGR-IV, (4) shading at the peak flower (PF) stage (12 days after FF) without PGR-IV, (5) shading at PF with PGR-IV, (6) shading at the boll development (BD) stage (24 days after FF) without PGR-IV, and (7) shading at BD with PGR-IV. Shade duration was 8 days for all shade treatments. Based on 1993 treatments, three additional treatments of no shading with PGR-IV, shading at the floral bud/pinhead square (PHS) stage with PGR-IV, and shading at PHS without PGR-IV were added in 1994.

In 1995, the three 8-day shade treatments were (1) shading at the PHS stage, (2) shading at 8 days after the PHS, and (3) shading at 16 days after the PHS to determine plant response to shade and PGR-IV before flowering. In this study the PHS and FF stages were defined as the date when 50% of the plants in a plot had visible floral buds (squares) and first white flowers, respectively. Each shade treatment was split with and without PGR-IV. Experiments were arranged in a split-plot design with three replications. Shade treatment factors were main-plots, and PGR-IV treatments were subplots.

The shade shelters were made from PVC pipe 5 cm in diameter with black shade cloth (Hummert Seed Co., St. Louis, MO) providing a 63% sunlight reduction. Photosynthetic photon flux density (PPFD) of shade treatments was about 37% of the PPFD of unshaded control (full sunlight). PGR-IV was applied foliarly twice at a rate of 292 mL ha^{-1} in 47 liters of water with a calibrated CO_2-pressurized backpack sprayer at PHS and 5 days before FF for PGR-IV treatments.

During the experiment, fruit abscission was counted daily in 1993, and the photosynthetic rate of the uppermost fully expanded main-stem leaves was measured between 1130 h and 1300 h central daylight saving time (CDST) with an LI-6200 portable photosynthesis system (LI-COR Inc., Lincoln, NE). Thereafter, 12 fresh leaf discs, each 0.38 cm^2, were cut from six leaves of each plot after measuring photosynthesis (two discs/leaf) at 1300 h (CDST). Half of the discs from the six leaves were dried to obtain dry weight (DW), and the remaining were used to extract chlorophyll using the method of Cornish et al. (1991). The six discs sampled from six plants used to quantify chlorophyll within a treatment plot were placed into a test tube containing 5 mL of 800-mL acetone/liter and stored at −19°C in darkness. After all color had been extracted from the discs, the solution was diluted to 10 mL, and chlorophyll concentrations were determined using a spectrophotometric method (Arnon 1949).

The ten uppermost fully expanded main-stem leaves, and bracts and floral buds of ten 20-day-old squares at the first fruiting position of sympodial branches from each plot were sampled at 1300 h (CDST) at 2, 4, 6, and 8 days after the initiation of shade treatments. The samples were killed at 90°C for 30 min, dried at 70°C for 72 h, ground, and passed through a 0.5-mm sieve for analysis of nonstructural carbohydrates (hexose, sucrose, and starch). The modified method of Hendrix (1993) was used to extract and quantify nonstrucutral carbohydrates from 10 mg of the ground dry samples. Sample solutions were centrifuged at $3{,}000 \times g$ for 15 min after each extraction to separate the supernatant and insoluble material. The nonstructural carbohydrate concentrations were expressed as g/kg dry weight (g kg^{-1} DW). The sum of hexose, sucrose, and starch was defined as total nonstructural carbohydrate (TNC). At harvest, the number of bolls, the seedcotton weight, and the lint weight were determined. The lint yield, lint percentage, and average seedcotton weight/boll (boll weight) were calculated to analyze the effects of shading at the different growth stages on yield and yield components of cotton with and without PGR-IV.

All data were subjected to analysis of variance. The means of main effects of shade and PGR-IV treatments were significant (F tests, $p < 0.05$), but the interactions between shade and PGR-IV were not significant ($p > 0.05$). Therefore, the tests of a least significant difference (LSD) were used to determine if differences among the treatment means were significant ($p < 0.05$).

Results and Discussion

Photosynthetic Rate and Fruit Abscission

Under conditions of 63% shade of field-grown cotton plants during flowering and boll development, the photosynthetic rate of the uppermost fully expanded main-stem leaves decreased by 28–48%, chlorophyll concentration increased by 8–13%, and fruit abscission in 20 days after the initiation of the shade increased by 97–267% (Table 1). Foliar application of PGR-IV did not significantly influence leaf photosynthetic rate or chlorophyll concentration of shaded cotton.

Compared with shaded plants without PGR-IV, the fruit abscission of shaded cotton plants with PGR-IV application was decreased by 37, 41, and 12% at the FF,

Table 1. Effects of an 8-day period of shade at different growth stages and PGR-IV application on leaf net photosynthetic rate, leaf chlorophyll concentrations, and fruit abscission of field-grown cotton. Photosynthetic rate and chlorophyll were measured in 1994; fruit abscission was recorded in 1993 at Fayetteville, Arkansas.

Treatments	Net photosynthetic rate (μmol CO_2 m^{-2} s^{-1})	Chlorophyll concentration (μg cm^{-2})	Fruit abscission (no. m^{-1} row)
First flower stage			
Control	28.8 a*	43.4 b	24 c
Shade†	15.3 b	46.9 a	51 a
PGR-IV‡	29.9 a	44.0 b	— §
Shade + PGR-IV	15.6 b	49.9 a	32 b
Peak flower stage			
Control	23.7 a	41.3 c	30 c
Shade	12.4 b	45.9 ab	59 a
PGR-IV	24.6 a	43.3 bc	—
Shade + PGR-IV	12.9 b	47.1 a	35 b
Boll development stage			
Control	16.2 a	40.5 b	18 b
Shade	11.6 b	45.9 a	66 a
PGR-IV	14.5 a	42.1 b	—
Shade + PGR-IV	10.1 b	46.6 a	58 a

* The data with the same letter within a growth stage in the same column are not significantly different (p > 0.05).

† Light intensity of all shade treatments at the three growth stages was reduced 63% compared with unshaded control.

‡ PGR-IV was applied foliarly twice at both the pinhead square stage and 5 days before the first flower stage.

§ This treatment was not included in 1994.

PF, and BD stages, respectively (Table 1). This could provide a significant crop management advantage in areas where periods of cloudy, overcast weather frequently occur. Guinn (1976, 1982) showed that low light considerably increased ABA and ethylene concentrations of 4- to 11-day-old cotton bolls and suggested that this may be a causal factor in boll abscission. Because PGR-IV contains GA and IBA, both of which can antagonize the actions of ABA and ethylene (Benedict 1984), it is speculated that foliar application of PGR-IV before shade may partially alleviate the detrimental effect of ABA and ethylene on fruit abscission.

Nonstructural Carbohydrates

An 8-day period of shade at the PHS, FF, PF, and BD stages in 1994 caused a 48, 47, 70, and 62% decrease in TNC concentration, respectively (Fig. 1). Leaf starch concentration was reduced the most by the shade treatment (60% averaged over the four growth stages), and hexose was reduced the least (27%) of the three nonstructural carbohydrate components. Under no-shade conditions, PGR-IV-treated plants showed significantly lower leaf TNC concentrations than control plants without PGR-IV at the PHS and FF stages, whereas the carbohydrate concentrations did not differ between the two treatments at the PF and BD stages. Under shade conditions, there was no significant difference in leaf TNC concentration between plants treated with and without PGR-IV, except at the BD stage, at which shaded plants with PGR-IV had a significantly higher TNC concentration than shaded plants without PGR-IV (Fig. 1). The results of leaf carbohydrate measurement in 1995 were similar to those in 1994 (data not shown).

The TNC concentration in the bracts of 20-day-old squares in 1994 (Fig. 2) was only a third of that in the leaves (Fig. 1) under no-shade conditions. However, the proportion of sucrose in the TNC of bracts was much higher than that of the leaves at the FF and PF stages (Figs. 1 and 2). For example, leaf sucrose concentration accounted for only 8% of leaf TNC concentration, whereas bract sucrose concentration accounted for 33% of bract TNC concentration. A high fraction of sucrose in bracts is probably beneficial to carbohydrate translocation from bracts to fruiting forms (Benedict and Kohel 1975). The overall responses of the carbohydrate concentrations in the bracts to shade and PGR-IV were similar to those in leaves. Shade significantly decreased the TNC concentration of bracts. Under shade conditions, however, when averaged over the three growth stages, the bracts had a smaller decrease in the TNC concentration (44%) than the leaves (60%). The TNC concentration in the bracts of shaded cotton with PGR-IV application was significantly higher compared with that of shaded cotton without PGR-IV at the PF and BD stages.

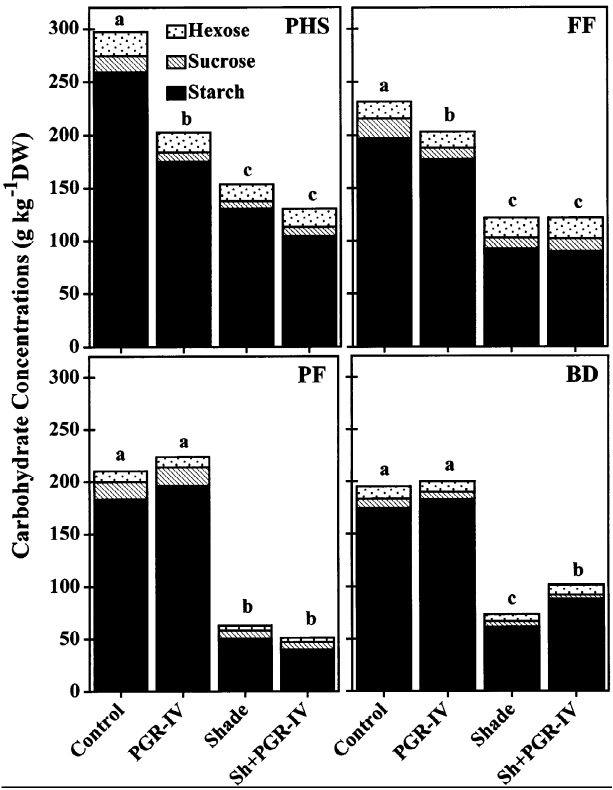

Fig. 1. Effects of PGR-IV application and an 8-day period of shade at different growth stages on nonstructural carbohydrate concentrations in leaves of field-grown cotton plants in 1994 in Fayetteville, Arkansas. *Bars* with the same *letter* within a stage are not significantly different for TNC concentrations ($p > 0.05$).

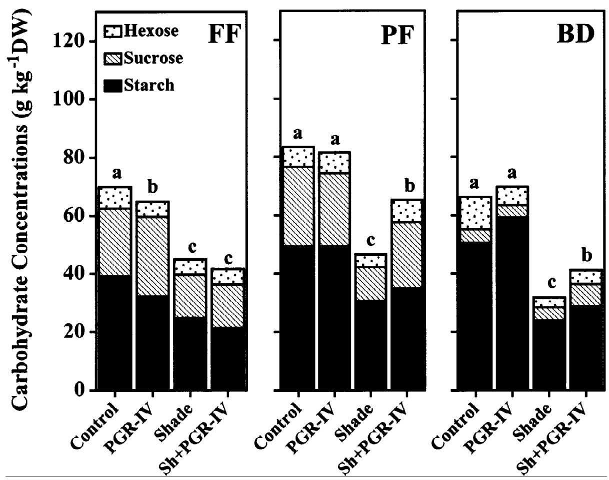

Fig. 2. Effects of PGR-IV application and an 8-day period of shade at different growth stages on nonstructural carbohydrate concentrations in the bracts of 20-day-old squares of field-grown cotton plants in 1994 in Fayetteville, Arkansas. *Bars* with the same *letter* within a stage are not significantly different for TNC concentrations ($p > 0.05$).

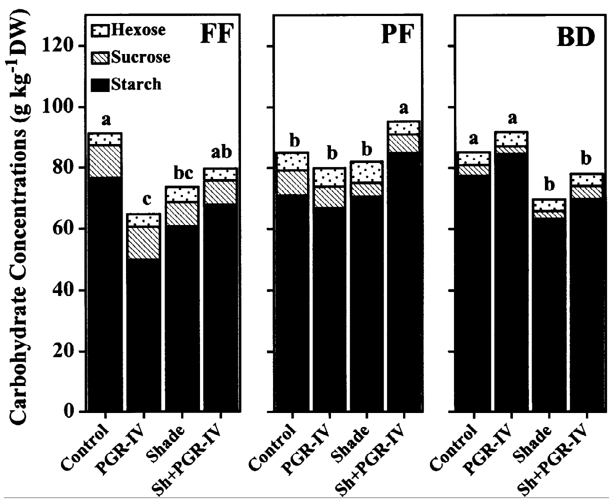

Fig. 3. Effects of PGR-IV application and an 8-day period of shade at different growth stages on nonstructural carbohydrate concentrations in the floral buds of 20-day-old squares of field-grown cotton plants in 1994 in Fayetteville, Arkansas. *Bars* with the same *letter* within a stage are not significantly different for TNC concentrations ($p > 0.05$).

The nonstructural carbohydrate concentrations in 20-day-old floral buds (Fig. 3) exhibited a smaller change between treatments compared with those of leaves (Fig. 1). Similar to the TNC in the leaves, the TNC concentration in the floral buds of unshaded plants with PGR-IV was significantly lower than that of unshaded control plants without PGR-IV at the FF stage but did not differ between these two treatments at the PF and BD stages. Under shade conditions, no statistical differences were observed in the TNC concentration of floral buds between PGR-IV-treated and untreated plants.

Under no-shade conditions, PGR-IV-treated plants had significantly lower leaf nonstructural carbohydrate concentration than control plants without PGR-IV at the PHS and FF stages (Fig. 1). This result might be associated with improved translocation of assimilate from leaves to fruits due to PGR-IV (Guo and Oosterhuis 1995). The PGR-IV-treated plants also had a lower floral bud carbohydrate concentration than the untreated plants (Fig. 3), which would not support the explanation of Guo and Oosterhuis (1995) that PGR-IV improved carbohydrate translocation from source (leaves) to sink (buds). Heitholt and Schmidt (1994) reported that although high assimilate flux into developing cotton fruits might be expected to be associated with high assimilate concentrations, it was also possible that the high assimilate flux into developing fruits might be associated with rapid metabolic activity and thus, low assimilate concentrations. The low floral bud carbohydrate concentration of PGR-IV-treated plants may therefore be explained by rapid metabolic activity of the buds. Shaded plants with

Table 2. Effects of an 8-day period of shading at first flower (FF), peak flower (PF), and boll development (BD) stages on lint yield and yield components of cotton with and without PGR-IV in 1993 at Fayetteville, Arkansas.

Treatments	Lint yield (kg ha^{-1})	Boll number (no. m^{-2})	Boll weight (g $boll^{-1}$)	Lint percentage (%)
Control	810 a*	60.5 a	3.39 a	39.5 b
FF shading	661 ab	49.5 abc	3.41 a	39.2 b
FF shading + PGR-IV	781 a	60.0 ab	3.36 a	38.7 b
PF shading	534 bcd	39.5 c	3.53 a	38.3 b
PF shading + PGR-IV	604 abc	45.4 bc	3.42 a	38.9 b
BD shading	387 d	35.5 c	2.64 b	41.3 a
BD shading +PGR-IV	439 cd	42.0 c	2.52 b	41.5 a

* Values with the same letter within a column are not significantly different ($p > 0.05$).

Table 3. Effects of an 8-day period of shading at pinhead square (PHS), first flower (FF), peak flower (PF), and boll development (BD) stages on lint yield and yield components of cotton with and without PGR-IV in 1994 at Fayetteville, Arkansas.

Treatments	Lint yield (kg ha^{-1})	Boll number (no. m^{-2})	Boll weight (g $boll^{-1}$)	Lint percentage (%)
Control	1,103 ab*	69.8 ab	4.04 abc	39.2 ab
PGR-IV	1,149 a	75.8 a	3.75 c	40.4 a
PHS shading	1,025 abc	60.7 cde	4.26 a	39.6 ab
PHS shading + PGR-IV	1,085 ab	69.8 ab	3.91 abc	40.0 a
FF shading	903 cd	59.6 bcd	4.01 bc	37.8 ab
FF shading + PGR-IV	1,018 abc	64.9 bc	4.16 ab	37.8 b
PF shading	878 cd	53.7 de	4.11 abc	39.9 a
PF shading + PGR-IV	980 bcd	62.5 bc	3.93 abc	39.3 ab
BD shading	779 d	52.7 e	3.81 abc	38.9 ab
BD shading + PGR-IV	902 bcd	62.9 bc	3.64 bc	39.4 ab

* Means with the same letter within a column are not significantly different ($p > 0.05$).

PGR-IV had higher TNC concentrations in the floral buds than shaded plants without PGR-IV (Fig. 3). The higher bud carbohydrate concentration might be an important factor resulting in a lower fruit abscission for shaded cotton plants treated with PGR-IV (Table 1).

Lint Yield and Yield Components

When plants were shaded at the FF stage in 1993 (Table 2) or PHS stage in 1994 (Table 3) and in 1995 (data not shown), lint yield did not differ statistically between shaded and unshaded plants. However, when plants were shaded at the PF and BD stages, lint yield decreased significantly ($p < 0.05$) in 1993 and 1994. The decrease in lint yield of shaded cotton was associated primarily with decreased boll number caused by high fruit abscission during shading (Tables 2 and 3). This finding is consistent with the report by Pettigrew (1994) who also found that the low yield of shaded cotton was attributed mainly to a lower boll number/unit of land area.

Lint yield was not statistically different between shaded plants with and without PGR-IV within a growth stage, although shade treatments with PGR-IV showed a numerically higher yield (13–18% in 1993, and 6–17% in 1994) than treatments without PGR-IV (Tables 2 and 3). In 1993, the application of PGR-IV did not significantly affect yield components of shaded cotton. However, in 1994 the plants treated with PGR-IV had significantly higher boll numbers than the shaded plants without PGR-IV (Table 3). The application of PGR-IV did not affect lint percentage of shaded cotton.

Overall, the application of PGR-IV before shade reduced fruit abscission caused by shading (Table 1) and increased boll retention (Table 3). This may have been associated with PGR-IV improving assimilate translocation from leaves to fruits as Guo and Oosterhuis (1995) have shown for soybean. Applying PGR-IV was found to increase boll retention of shaded cotton but did not significantly improve lint yield compared with shaded cotton without PGR-IV. This was because the advantage of increased boll numbers in shaded plants with PGR-IV was negated by the smaller average boll weight compared with shaded plants without PGR-IV.

Conclusions

Shade during flowering and fruiting significantly increased leaf chlorophyll concentration, decreased leaf net photosynthetic rate and nonstructural carbohydrate concentration. As a result, fruit abscission increased by 97–267%, and lint yield decreased by 18–52%. Foliar application of PGR-IV before shade did not improve the leaf photosynthetic rate of shaded plants but did decrease the fruit abscission of shaded cotton, resulting in a numerical trend for a 6–18% higher lint yield compared with shaded plants without PGR-IV. The decreased fruit abscission from PGR-IV was probably associated with improved carbohydrate partitioning and plant hormone balance. Further research is needed to determine the influence of PGR-IV on carbohydrate translocation and change in hormone balance of cotton.

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