Effects of Glyphosate on *Calonectria crotalariae* and Red Crown Rot of Soybean

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ABSTRACT

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Surfactant- and nonsurfactant-containing commercial herbicide formulations of glyphosate were evaluated for in vitro and in vivo effects on *Calonectria crotalariae* and red crown rot of soybean, respectively. Rates of 0.28, 0.56, 1.12, and 2.25 kg of glyphosate per hectare, corresponding to recommended rates for weed control in soybean (*Glycine max*), were used. Three pathogenic isolates of the fungus from soybean were grown on a selective medium amended with either water or the different rates of the herbicide. Both formulations of glyphosate inhibited mycelial growth by *C. crotalariae*. Additions of amino acids to medium amended with the nonsurfactant formulation produced a reversal of herbicide inhibition. Duplicated field trials showed a reduction in red crown rot incidence with preplant applications of low rates of glyphosate. These results, coupled with findings on the significant influence of previous season disease incidence on current red crown rot levels, indicate that glyphosate may be used simultaneously and efficaciously as a preplant herbicide for weed control and as a fungicide for the control of diseases caused by *C. crotalariae*.

Additional keywords: Cylindrocladium black rot, peanut

Calonectria crotalariae (C. A. Loos) D. K. Bell & Sobers (imperfect stage = *Cylindrocladium crotalariae* (C. A. Loos) D. K. Bell & Sobers) (3) causes the diseases Cylindrocladium black rot (CBR) and red crown rot (RCR) on peanut (*Arachis hypogaea* L.) and soybean (*Glycine max* (L.) Merr.), respectively (4,12). Losses attributable to CBR on peanuts have been estimated to be as high as 53% (10), and a 50% yield loss can be expected on susceptible soybeans with 100% RCR incidence (4).

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The fungus overwinters in soil and crop debris as small (35–425 μm in diameter), irregularly shaped microsclerotia that function as initial inoculum (11,13). The role of ascospores and conidia in the disease cycles is unknown, although they may serve to colonize soil organic matter (8). Control measures for both diseases include the use of resistant varieties (2,4,16) and practices directed toward avoiding or reducing initial inoculum such as delayed planting (4,15) and, in the case of peanuts, soil fumigation (2). Because of the expense of soil fumigation, its use is the basis of an economic decision-making model for peanut growers (2). Fungicides that can economically control RCR have not been identified.

For the past 3 yr, we have used herbicides containing glyphosate for preplant weed control in RCR field studies. The field studies have relied on naturally occurring inoculum of *C. crotalariae* and, over time, a noticeable association between weed numbers and incidence of RCR developed. Weed-free areas were disease-free and weed-infested areas had high RCR incidence. Herbicides containing glyphosate have some

fungicidal activity (5,6,9,14), but often the fungicidal activity is attributed to the surfactant contained in some of these herbicides (5,14).

The biosynthesis of phenylalanine, tyrosine, and tryptophan in plants is blocked by glyphosate, which inhibits the conversion of shikimate to chorismate (a precursor of these amino acids) (1). Additions of these amino acids to plant tissue culture media has reversed the effects of glyphosate (7). If fungitoxic effects of glyphosate formulations on *C. crotalariae* could be affected similarly, this would suggest that glyphosate alone is responsible for the fungitoxic activity.

From past field studies, a significant positive relationship was established between previous and current season RCR incidence (D. K. Berner, *unpublished*). If preplant applications of commercial glyphosate formulations could be shown to reduce levels of RCR within a growing season, a novel and economical usage for the herbicide would be to provide preplant weed control while simultaneously and cumulatively reducing annual levels of RCR.

The first objective of this study was to determine if recommended herbicidal rates of commercial formulations of glyphosate would inhibit growth of *C. crotalariae* in vitro. Further objectives were to determine what rates were most fungitoxic and whether isolates of *C. crotalariae* were affected similarly. Also, we wanted to determine if glyphosate or some other ingredient in the commercial formulations was the fungitoxic agent. Finally, we wanted to assess the field efficacy of different recommended rates of glyphosate on RCR incidence.

MATERIALS AND METHODS

In vitro studies. *Fungal isolates.* One pathogenic isolate of *C. crotalariae* was collected from soybean plants with RCR symptoms in each of three areas in Louisiana (MSES = Maringouin, BS = Burnside, and STJ = St. James) and isolated on Phipps' semiselective medium (11). Hyphal tips from each isolate were transferred to cornmeal agar amended with 2% (v/v) glycerol. One isolate (MSES) was chosen to conduct the initial herbicide screening. The other two isolates were later tested against the 2.25 kg/ha rate of glyphosate.

Culture medium. The medium used for the herbicide studies was Phipps' semiselective medium (11) without thiabendazole. Aliquots (100 ml) of liquified medium were measured into 250-ml Erlenmeyer flasks. The medium was then autoclaved and allowed to cool to 45 C before adding amendments. Each amendment was added to the medium by sterile pipet. For each treatment, 10 petri dishes, each containing 10 ml of amended medium, were prepared.

Treatments. Glyphosate at 0.56 kg/ha was considered a 1× rate for these studies. This corresponds to 0.86 g of glyphosate per liter of medium. Both Roundup (41.0% isopropylamine salt of glyphosate, Monsanto Company, Agricultural Products, St. Louis, MO), which contains a surfactant, and Rodeo (53.8% isopropylamine salt of glyphosate, Monsanto), which does not contain surfactant, were evaluated. Amounts of herbicide needed to approximate field rates were calculated based on the surface area of the medium contained in a 90-mm-diameter petri dish. Aqueous stock solutions of the formulated herbicides were prepared so that rates approximating 0.5×, 1×, 2×, and 4× could be tested by varying the amount of solution added to the medium. Final concentrations for 1× were 0.74 μl of Roundup per milliliter of medium and 0.60 μl of Rodeo per milliliter of medium. To compensate for possible dilution effects, control treatments were made by adding appropriate amounts of sterile distilled water, in lieu of herbicide, to the medium.

To simulate a repeat application of herbicide, 4-mm-diameter mycelial plugs from treated 4-wk-old cultures of *C. crotalariae* were transferred to fresh identically amended medium. The medium was prepared as described and 10 petri dishes were prepared for each treatment. This procedure was done sequentially to form original (first) and second cycle cultures. All cultures were grown in natural light at ambient temperature.

Aqueous stock solutions of DL-phenylalanine (PHE), DL-tyrosine (TYR), and DL-tryptophan (TRP) were made in 0.1 M concentrations. To determine if the herbicide effects could be reversed by additions of amino acids, 3 ml of these solutions was added to medium prepared at the 4× rate of 3.44 g of glyphosate per liter of medium (2.25 kg of glyphosate per hectare). The amino acids were added singly and in all combinations. Treatments of two amino acids received 6 ml of total amendment per 100 ml of medium (3 ml of each amino acid), and the treatment with all three amino acids received a total of 9 ml per 100 ml of medium. Controls included herbicide + no amino acid (9 ml HOH), no herbicide (8 ml HOH) + each of the above amendments, and no herbicide (8 ml HOH) + no amino acid (9 ml HOH). Preliminary tests with herbicides, antibiotics, and water, each filtered through 0.2-μm sterile syringe filters, produced the same results as unfiltered amendments (D. K. Berner, *unpublished*). This experiment was conducted with the MSES isolate and the surfactant-containing glyphosate formulation (Roundup), and, to test the effects of surfactant on fungal growth, the experiment was also conducted twice with the MSES isolate and the nonsurfactant formulation (Rodeo).

Analyses. Maximum colony diameter was measured after 2 wk of fungal growth. Colony area was then calculated. The rate-response experiment was conducted twice and analyzed as a randomized complete block design with trials as blocks. All other experiments were analyzed as completely randomized designs. Because response to individual rates was of interest, treatment means were plotted with their associate standard errors. For these results to be readily translateable with the results of the in vivo studies, rates are expressed as equivalent weights of glyphosate per hectare.

In vivo studies. *Locations.* Two fields (in St. Gabriel and Burnside, LA) with a history of RCR were used. The Burnside location had been used extensively in the past for RCR studies, and the St. Gabriel location was known to have a high level of infestation of soil by *C. crotalariae.*

Treatments. The commercial glyphosate formulation used in this study was Roundup. Three glyphosate treatments were application rates of 0.56, 1.12, and 2.25 kg of glyphosate per hectare. These rates correspond to the 1×, 2×, and 4× rates used in the in vitro experiments. Treatments were applied immediately before planting. After application, four 1 × 12 m rows of the RCR-susceptible soybean cultivar Centennial were planted in each treatment plot. Each treatment was replicated eight times in each location in a completely randomized design. Because disease data were available from the previous season at Burnside, the previous season's disease ratings were used as a covariate at this location to adjust for plot differences in initial inoculum.

In addition to the herbicide treatments, three control treatments were used to determine both differences directly attributable to the herbicide and those attributable to weed densities. The control plots received no preplant glyphosate but received either zero, one, or two postemergence applications of fomesafen plus fluazifop-P-butyl. Each of these controls were replicated eight times in each location. All of the glyphosate treatments received two postemergence applications of fomesafen plus fluazifop-P-butyl for weed control. A general preplant application of pendimethalin was used at the St. Gabriel location. No general preplant herbicide application was used at Burnside.

Data collection and analyses. RCR incidence in each plot was determined by counting the number of plants with *C. crotalariae* perithecia out of the total number of plants within a randomly selected linear meter of row. Random selections were accomplished by generating random numbers that coincided with steps into the plot area. At this number of steps, the percent RCR incidence was determined. This procedure was conducted eight times for each plot, and the individual samples were averaged to form a plot mean. These means were then analyzed by analysis of variance or

covariance and least square means and standard errors were generated for each treatment. Yield was measured by harvesting the middle two rows of each plot, weighing the seed, adjusting the weights to 13% moisture content, and expressed as kilograms per hectare. Analysis of variance was carried out on individual plot yields.

RESULTS

In vitro studies. Colony areas of the control treatments did not significantly decrease in either cycle with increasing HOH additions (Fig. 1). In both cycles, glyphosate amendments greatly reduced colony area compared with that of the controls. In cycle 1, there was approximately an 80% reduction in colony area with the 4× (2.25 kg/ha) rate compared with the unamended control. In cycle 2, this reduction was approximately 60%. The effect of the herbicide was significant at the lowest rates included in each cycle. In cycle 2, the 0.5× rate was not included because the cultures were inadvertently contaminated. The differences in the water controls between the two cycles were probably attributable to differences in ambient temperature (caused by faulty air conditioning) at which the cultures were grown.

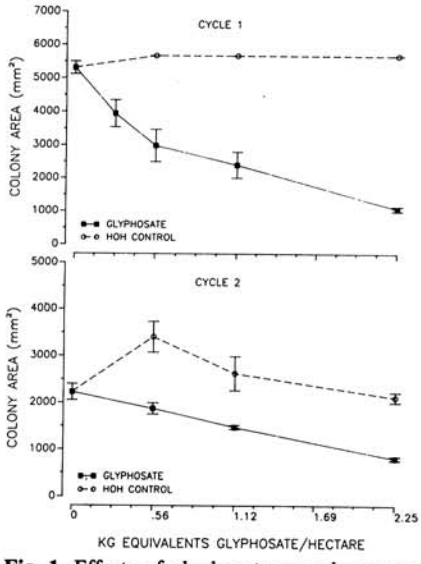

Fig. 1. Effects of glyphosate on colony area of *Calonectria crotalariae* after 2 wk of growth. Data points are an average of measurements of colony diameter on a semiselective medium (11) without thiabendazole in 10 petri dishes per trial and two trials. Standard error bars are indicated. Standard error for cycle 1 HOH control = 0.0.

All three isolates grown on medium with the 2.25 kg/ha rate of glyphosate as Roundup (Table 1) responded similarly. The smaller colonies of all isolates grown on the herbicide-amended medium appeared to be more darkly pigmented than colonies grown on the control medium (Fig. 2), and they also appeared to have produced fewer microsclerotia per unit area. Growth of the colonies was not uniform across the herbicide-amended medium, which resulted in colonies that had a branched appearance (Fig. 2).

Both surfactant- and nonsurfactant-containing herbicides reduced colony area significantly (Tables 2–4). Colonies grown on medium amended with the glyphosate formulation containing surfactant (Roundup) averaged 42% of the area of the water controls. Colonies grown on medium amended with the herbicide without surfactant (Rodeo) produced colonies that averaged 55 and 22% of the controls in the two trials, respectively. With the exception of the second trial with Rodeo, the additions of amino acids generally seemed to result in increased colony area of the water control treatments. In the second Rodeo trial, the colonies in most of the water control treatments had grown to the edge of the petri dishes, and enhancement of growth by amino acid additions was impossible to discern. In general, *C. crotalariae* responded favorably to the additions of the amino acids putatively inhibited by glyphosate.

Additions of amino acids to Roundup-amended medium failed to result in colony sizes equal to those in the water controls, and, only in the case of the tyrosine plus tryptophan treatment did the amino acid additions significantly increase colony area of the herbicide-amended treatment over that of the control with no amino acid addition (Table 2). With the exception of the tyrosine treatment in the Rodeo-amended medium in trial 1 (Table 3), all of the amino acid additions resulted in significantly larger colonies than the herbicide-amended medium with no amino acid addition. Fungal growth in the Rodeo-amended medium, containing additions of all three amino acids, did not differ significantly from the water control in trial 1. Growth in this treatment was also the greatest among all of the herbicide-amended treatments. This seemed to indicate a reversal of the herbicidal effect, but, because the respective water control was significantly smaller than all of the other water controls, the experiment was repeated.

In the second trial with Rodeo (Table 4), the addition of all three amino acids to the herbicide-amended medium also resulted in the greatest fungal growth among the herbicide-amended treatments. Although fungal growth in all of the herbicide-amended treatments was significantly less than the water controls, the herbicide treatment with the addition of all three amino acids resulted in radial growth over twice that of the herbicide treatment with no amino acid addition. With the exception of the tyrosine, tryptophan, and the tyrosine + tryptophan treatments, all of the other amino acid treatments also resulted in significantly larger colonies than the herbicide treatment with no amino acid.

Orthogonal contrasts were generated to compare the effects of each amino acid on the heribicide treatments. From these contrasts, we concluded that colonies in treatments containing phenylalanine and/or tryptophan were, on the average, significantly larger in both trials than the treatments containing tyrosine.

In vivo studies. There were no significant differences in RCR incidence among the three control treatments at

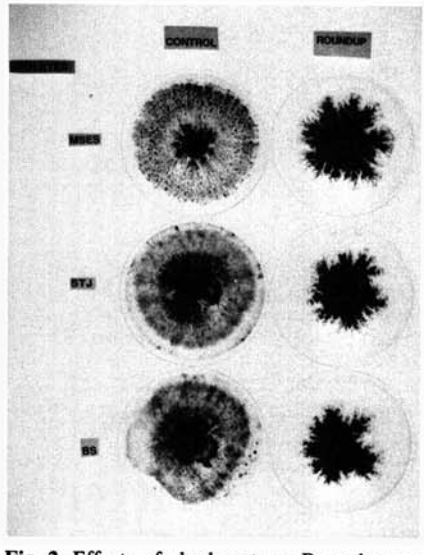

Fig. 2. Effects of glyphosate as Roundup on colony development of three isolates of *Calonectria crotalariae* after 2 wk of growth on a semiselective medium (11) without thiabendazole. Glyphosate rate is the equivalent of 2.25 kg of glyphosate per hectare. HOH controls contain 8 ml of water per 100 ml of medium.

Table 1. Least square means of 2-wk-old colony area (mm^2) for three isolates of *Calonectria crotalariae* grown in a semiselective medium amended with either 8 ml of stock herbicide solution (2.25 kg/ha of glyphosate as Roundup) or 8 ml of HOH per 100 ml of medium

Isolate[a]	Roundup	HOH	$LSD_{0.05}$
MSES	926.9	2,376.8	215.6
BS	735.0	1,809.6	51.7
STJ	725.7	1,566.5	184.6
$LSD_{0.05}$[b]	93.2	355.9	
LS mean	795.9	1,917.6	117.9

[a]MSES = isolate taken from Maringouin, LA; BS isolate from Burnside, LA; and STJ = isolate from St. James, LA.
[b]LSD within columns based on harmonic mean of cell sizes.

either field location. Data from the three controls per location were pooled for subsequent analysis. Preplant applications of glyphosate as Roundup reduced RCR incidence at the 0.56 kg of glyphosate per hectare rate in both locations (Fig. 3). The reduction was substantial but nonsignificant at the St. Gabriel location, and higher application rates resulted in RCR incidences that were as great or greater than the controls.

Regression analysis of 2 yr of RCR incidence data from the Burnside location showed previous season disease incidence to be a positive and highly significant indicator of current season disease levels. When previous season disease incidence was used as a covariate to adjust initial disease levels at the Burnside location, a reduction in RCR incidence was seen at all preplant glyphosate application rates. This reduction was greatest at the 1.12 kg/ha rate where there was a clear separation of standard error bars, representing a significant difference at $P = 0.16$. When data from the two locations was combined (without benefit of the covariate), the greatest reduction in RCR incidence was seen at the 0.56 kg/ha rate, which was a significant reduction at $P = 0.13$. The data combined from both locations also showed a trend toward higher disease incidence at the higher application rates. There were no significant differences in yield among any of the treatments at any of the locations.

Table 2. Least square means of 2-wk-old colony area (mm^2) for *Calonectria crotalariae* when treated with combinations of DL-phenylalanine (PHE), DL-tyrosine (TYR), and DL-tryptophan (TRP) in media amended with either 8 ml of stock herbicide solution (2.25 kg/ha of glyphosate as Roundup) or 8 ml of HOH per 100 ml of medium

Amino acid	Roundup	HOH	$LSD_{0.05}$
PHE	651.1	1,505.8	275.9
TYR	851.8	1,739.5	275.9
TRP	684.1	2,282.8	275.9
PHE + TYR	455.6	1,857.0	283.4
PHE + TRP	543.0	1,185.3	275.9
TYR + TRP	883.7	1,683.7	275.9
PHE + TYR + TRP	710.0	1,685.5	318.6
None[a]	704.0	1,124.3	283.4
$LSD_{0.05}$[b]	149.1	388.6	
LS mean	685.4	1,633.0	100.2

[a]Treatments with no amino acid received 8 ml of the respective amendment + 9 ml of HOH.
[b]LSD within columns based on harmonic mean of cell sizes.

Table 3. Least square means of 2-wk-old colony area (mm^2) for *Calonectria crotalariae* when treated with combinations of DL-phenylalanine (PHE), DL-tyrosine (TYR), and DL-tryptophan (TRP) in media amended with either 8 ml of stock herbicide solution (2.25 kg/ha of glyphosate as Rodeo) or 8 ml of HOH per 100 ml of medium in trial 1

Amino acid	Rodeo	HOH	$LSD_{0.05}$
PHE	1,781.9	3,583.8	352.0
TYR	1,584.5	4,027.8	352.0
TRP	1,880.6	3,393.2	352.0
PHE + TYR	1,915.2	3,831.0	352.0
PHE + TRP	1,767.3	3,531.8	352.0
TYR + TRP	1,976.8	3,311.7	352.0
PHE + TYR + TRP	2,079.4	1,886.5	352.0
None[a]	1,567.5	2,844.6	352.0
$LSD_{0.05}$[b]	154.1	479.6	
LS mean	1,819.2	3,301.3	124.5

[a]Treatments with no amino acid received 8 ml of the respective amendment + 9 ml of HOH.
[b]LSD within columns based on harmonic mean of cell sizes.

Table 4. Least square means of 2-wk-old colony area (mm^2) for *Calonectria crotalariae* when treated with combinations of DL-phenylalanine (PHE), DL-tyrosine (TYR), and DL-tryptophan (TRP) in media amended with either 8 ml of stock herbicide solution (2.25 kg/ha of glyphosate as Rodeo) or 8 ml of HOH per 100 ml of medium in trial 2

Amino acid	Rodeo	HOH	$LSD_{0.05}$
PHE	1,377.3	5,904.1	167.8
TYR	849.2	5,944.7	167.8
TRP	952.1	5,890.6	167.8
PHE + TYR	1,474.4	5,944.7	167.8
PHE + TRP	1,910.5	5,917.5	167.8
TYR + TRP	1,022.6	5,931.1	167.8
PHE + TYR + TRP	1,964.9	5,472.4	167.8
None[a]	953.5	5,944.7	167.8
$LSD_{0.05}$[b]	117.8	320.4	
LS mean	1,313.1	5,868.7	83.9

[a]Treatments with no amino acid received 8 ml of the respective amendment + 9 ml of HOH.
[b]LSD within columns based on harmonic mean of cell sizes.

DISCUSSION

The herbicides containing glyphosate used in this study greatly reduced growth of *C. crotalariae* in vitro and appeared to affect the degree of pigmentation and microsclerotia development. These effects were universal for the three isolates tested. The effect of increasing herbicide rates was additive, with the highest rates resulting in the smallest colonies. However, even low rates of herbicide reduced colony area significantly. These rates corresponded to field use rates of 0.28–0.56 kg of glyphosate per hectare, which are relatively low herbicide rates for preplant weed control in soybeans.

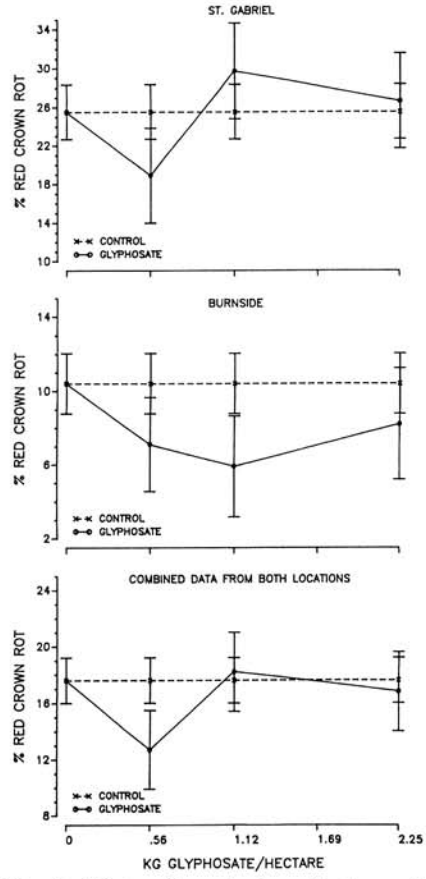

Fig. 3. Effects of preplant applications of glyphosate on incidence of red crown rot of soybean caused by *Calonectria crotalariae* in two field locations. Data points for each location are an average of eight replications per glyphosate application rate. Data points for the combined data are an average of 16 replications. Control data points are an average of three control treatments per location and represent 24 replications per location and 48 replications for the combined data. Standard error bars are indicated.

Simulated repeat applications of herbicide did not enhance the fungitoxic effect.

The addition of amino acids, particularly phenylalanine and tryptophan, initiated a reversal or blockage of the herbicide effect in the experiments with Rodeo. This indicates that glyphosate alone is fungitoxic to *C. crotalariae* and that the biosynthesis pathway for these amino acids is probably the same in *C. crotalariae* as it is in plants. The failure of the amino acid additions to completely block the activity of the herbicide was probably attributable to dosage differences between the 3.44 g/L glyphosate concentration and the 0.1 M amino acid concentration. Because additions of amino acids did not reverse any herbicidal effect in Roundup treatments, the surfactant contained in this formulation might have an additional fungitoxic effect that does not function in amino acid biosynthesis inhibition. We were unable to obtain a sample of the surfactant for direct testing.

The results of the in vivo studies are encouraging in two aspects. First, there was a direct reduction in disease incidence at the lowest rates in both locations which translated to a reduction ($P = 0.13$) in RCR incidence for the combined data. Because there were no differences among the controls, this reduction appears to be directly attributable to the fungitoxic effects of the herbicide rather than to any indirect role of weeds in RCR epidemiology. Although glyphosate is putatively degraded and/or immobilized by soil, it is translocated to the roots of target plants (5) and may have an effect on soil microflora in the target plant rhizosphere. It may be by this mechanism that low preplant rates of glyphosate inhibit *C. crotalariae* and RCR development. At higher rates, the herbicide may be less efficacious because of derogatory effects on soil microflora that are competitive with *C. crotalariae*.

Because there is a strong relationship between previous and current season RCR incidence, a second promising effect is cumulative reduction in RCR with preplant glyphosate applications being used over several seasons. The low rates at which glyphosate was effective present a novel and economic control strategy for *C. crotalariae*. Where RCR of soybean and CBR of peanut are major diseases, preplant weed control could be modified to include glyphosate. Glyphosate resistant cultivars would allow expansion of usage to pre- and postemergence weed and disease control.

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