Influence of Early-Season Nitrogen and Weed Management on Irrigated and Nonirrigated Glyphosate-Resistant and Susceptible Soybean

Larry G. Heatherly,* Stan R. Spurlock, and Krishna N. Reddy

ABSTRACT

Field studies were conducted on Sharkey clay soil (very-fine, smectitic, thermic Chromic Epiaquert) at Stoneville, MS (33°26′ N lat). The objectives were to determine the effect of application of 0 and 35 kg N ha^{-1} applied early in the growing season to glyphosate-resistant (GR) and non-GR soybean [*Glycine max* (L.) Merr.] cultivars using two weed management systems in irrigated and nonirrigated environments. Weed management systems were (i) pre-emergent followed by postemergent weed management using nonglyphosate herbicides applied to both GR and non-GR cultivars (PRE + POST) and (ii) postemergent weed management using glyphosate on GR cultivars and nonglyphosate herbicides on non-GR cultivars (POST). Applied N had no effect on weed management in or yield from soybean and lowered average net returns by $28 to $50 ha^{-1}. Average seed yields from the highest-yielding GR cultivar in 1999 and 2000 were 135 and 270 kg ha^{-1} more than 1999 and 2000 yields from a non-GR cultivar in the nonirrigated environment (all net returns were negative and yields $<$1500 kg ha^{-1}). In the irrigated environment, use of a non-GR cultivar compared with a GR cultivar resulted in a significant 200 and 250 kg ha^{-1} greater yield and greater profits in 2 of 3 yr. Use of PRE + POST compared with POST-only was not necessary for achieving greatest yield or net return with either non-GR or GR cultivars. Use of postemergent glyphosate always resulted in the cheapest weed control ($43 to $81 ha^{-1}), even with the greater cost for seed of GR cultivars included. There was no measured effect of glyphosate compared with nonglyphosate herbicides on GR cultivar yield.

During the past decade, advances in biotechnology coupled with plant breeding have resulted in the development of GR soybean cultivars for use in soybean production systems (Reddy et al., 1999; Reddy, 2001). Padgette et al. (1996) concluded that, except for tolerance to glyphosate, GR genotypes are substantially equivalent to parental lines and other soybean cultivars not tolerant to glyphosate. Reddy et al. (1999) and Reddy (2001) recently summarized the effects arising from use of GR soybean cultivars. Glyphosate is a nonselective herbicide that kills most annual and perennial grass and broadleaf weeds. Thus, there is no concern about a sequence of application as there is with nonglyphosate grass and broadleaf herbicides that kill either grass weeds or broadleaf weeds but not both. Weeds of the same species that differ in size can be controlled simply by increasing the rate of glyphosate. Thus, herbicide application timing for adequate weed control is of less concern than when using nonglyphosate herbicides. Because glyphosate has no carryover or soil persistence, producers can use a glyphosate-only weed management program with no concern for choice of rotational or following crops.

Glyphosate-resistant cultivars offer producers the flexibility to control a broad spectrum of weeds in soybean with no concern for crop safety (Reddy, 2001). Cost of weed control using a postemergence management program for GR cultivars should be less, even with the greater cost for seed of most GR cultivars (Reddy et al., 1999; Heatherly et al., 2002b). This could translate to increased profits if yields from GR cultivars are equal or nearly equal to those from non-GR cultivars. Use of GR cultivars should preempt the use of tillage and pre-emergent herbicides for weed management. The flexibility of using either nonglyphosate herbicides or glyphosate on GR cultivars increases management options for weed control when GR cultivars are used. Nonglyphosate herbicides applied to GR soybean in monocrop or corn (*Zea mays* L.)–soybean rotation systems do not adversely affect GR soybean (Nelson and Renner, 1999; Webster et al., 1999).

Glyphosate inhibits 5-enolpyruvylshikimate-3-phosphate synthase (EPSPS) and thus blocks aromatic amino acid synthesis (Amrhein et al., 1980). While GR soybean cultivars contain resistant EPSPS, *Bradyrhizobium japonicum*, the principal N-fixing bacterium for soybean, does not contain a resistant enzyme. Thus, glyphosate applied to GR soybean may interfere with the symbiotic relationship (King et al., 2001). In controlled-environment experiments, Reddy et al. (2000) found that 1.12 kg a.i. ha^{-1} glyphosate reduced number and fresh weight of soybean nodules in the absence of N but had no effect with added N. In greenhouse, growth chamber, and field studies, early applications of $\geq$1.68 kg ha^{-1} glyphosate generally delayed N_2 fixation and decreased soybean biomass and N accumulation (King et al., 2001). However, plants had recovered by 40 d after emergence. In growth chamber studies, N_2 fixation was more sensitive to water deficits in GR plants treated with glyphosate. In a 1-yr field study, soybean biomass was reduced by glyphosate applied to GR soybean at one of two locations; the location with the reduction had limited soil water. Yield was not consistently affected by glyphosate application. Conditions and treatments (like glyphosate) that adversely affect the symbiotic relationship may influence the sensitivity of N_2 fixation to water deficits. King et al. (2001) surmised from their results that glyphosate applied to GR soybean not only delayed N_2 fixation, but also increased sensitivity of N_2 fixation to soil water deficits. Their conjecture was based on

L.G. Heatherly, USDA-ARS, Crop Genet. and Prod. Res. Unit, P.O. Box 343, Stoneville, MS 38776; S.R. Spurlock, Dep. of Agric. Econ., P.O. Box 9755, Mississippi State, MS 39762; and K.N. Reddy, USDA-ARS Southern Weed Sci. Res. Unit, P.O. Box 350, Stoneville, MS 38776. Received 18 June 2002. *Corresponding author (lheatherly@ars.usda.gov).

Published in Agron. J. 95:446–453 (2003).

Abbreviations: EPSPS, 5-enolpyruvylshikimate-3-phosphate synthase; GR, glyphosate resistant; WMS, weed management system.

one year's field results from one location. Nelson and Renner (1999) and Elmore et al. (2001) found that glyphosate has no negative effect on GR soybean growth, development, or yield in the field.

Soybean grown on most soils does not respond to preplant N fertilization (Johnson, 1987; Varco, 1999; Hoeft et al., 2000). The exceptions cited by Johnson (1987) were applications made to soils that were somewhat poorly drained, low in organic matter, and/or strongly acid below the plow layer. Ferguson et al. (2000) summarized work from Nebraska that had positive responses to preplant N applications about half the time and determined that it was not possible to predict soybean response to N fertilizer based on soil properties. The situations with positive responses often either had very low residual N, low N mineralization capability, or soil pH so low that it inhibited nodulation and N fixation. In these cases, 56 to 112 kg N ha^{-1} increased yield potential. Kansas scientists found that soybean planted into large amounts of wheat (*Triticum aestivum* L.) residue responded to 11 to 22 kg ha^{-1} starter N because inorganic N is temporarily immobilized by soil microorganisms decomposing the straw (Whitney, 1997). They also found that soybean planted on recently leveled soils may respond to 33 to 45 kg N ha^{-1} because of low soil N. In most cases, N fertilization of soybean is an unnecessary expenditure (Varco, 1999; Hoeft et al., 2000). In addition, concentrations of N surrounding soybean roots can delay or impede nodulation (Gibson and Harper, 1985) and thus reduce N fixation.

Soybean, especially when not irrigated, provides relatively low gross return with a small margin for profit in the midsouthern USA (Heatherly and Spurlock, 1999; Williams, 1999). This small profit margin dictates that all inputs associated with production must be evaluated with respect to their likelihood of increasing profitability and that yield losses due to controllable pests such as weeds must be prevented within economic constraints. The objective of the producer is to control weeds adequately to maximize profits; however, inputs used for weed management in soybean represent a significant cost (Buhler et al., 1997; Johnson et al., 1997; Reddy and Whiting, 2000; Heatherly et al., 2001, 2002a). Weed management expenditures are almost always made before the onset of drought and without knowledge of ensuing moisture status for subsequent crop and weed development. This presents a challenge, especially in nonirrigated production systems that often result in low yield in the midsouthern USA.

Measuring the effect of glyphosate on GR cultivars will involve the use of nonglyphosate pre-emergent and postemergent herbicides on both non-GR and GR cultivars and glyphosate on GR cultivars. It will also involve the application of early-season N to both non-GR and GR cultivars that are grown under the same weed management system (WMS). The treatments used in this study address these criteria. This research was designed to determine if the perceived effect of glyphosate on the symbiotic relationship between N-fixing nodulating bacteria and GR soybean cultivars can be overcome with, or compensated for by, the addition of N soon after planting in the field. The objective was to compare the yield and economic return from GR and non-GR soybean cultivars where early-season N was applied before application of postemergent nonglyphosate and glyphosate herbicides in nonirrigated (low yielding) and irrigated (high yielding) environments in the midsouthern USA. Economic analysis of results was conducted to assess the profitability of two WMSs and added N. Seed yields and estimated costs and returns were used to generate budgets for the economic comparisons.

MATERIALS AND METHODS

Field studies were conducted from 1999 through 2001 at the Delta Research and Extension Center at Stoneville, MS (33°26′ N lat) on Sharkey clay soil. Sharkey is the dominant soil series in the lower Mississippi River valley alluvial flood plain and comprises about 1.2 million ha in Arkansas, Kentucky, Louisiana, Mississippi, Missouri, and Tennessee (Pettry and Switzer, 1996). The pH at the study site ranged from 6.8 to 7.3, and P and K levels were in the high category (Varco, 1999).

Separate nonirrigated and irrigated experiments were conducted using a randomized complete block design with four replicates each year. Treatments were arrayed in a split-plot factorial arrangement, with cultivar as the main plot and the combination of WMS and early-season N level as the subplot. Treatments were randomly assigned to plots at the beginning of the study period and remained in the same location thereafter to determine effects where the same WMS and N level were used continuously over a period of time.

Row width was 0.5 m, and seeding rate was 16 seed m^{-1} row, or about 50 kg ha^{-1} seed. Plots were 4 m wide (8 rows) and 22 m (irrigated) or 20.5 m (nonirrigated) long. All experiments were seeded into a stale seedbed (Heatherly and Elmore, 1983; Heatherly, 1999a) that had been tilled the preceding fall. Fall tillage consisted of chisel plowing 45 cm deep followed by shallow tillage (<10 cm deep) with a disk harrow and spring-tooth cultivator in 1998 and 1999 and shallow tillage with a disk harrow and spring-tooth cultivator in 2000. Glyphosate at 840 g a.i. ha^{-1} in 94 L ha^{-1} water was applied preplant to each experimental site each year to kill existing weed vegetation.

Non-GR and GR cultivars were used each year. They were non-GR 'AP 4880' in 1999 and 'AP 4882' in 2000 and 2001 and GR 'SG 468' and 'DP 4750' in 1999 and 'DP 4690' and 'AG 4702' in 2000 and 2001. Cultivars were chosen based on regional variety trial results, use patterns by producers, and recency of release. Cultivars were updated in 2000 to ensure that recently released, relevant cultivars that offered potentially improved performance were used. Planting dates were 17 May 1999, 28 Apr. 2000, and 2 Apr. 2001. Seed were treated with mefenoxam {(*R*)-2-[2,6-(dimethylphenyl)-methoxyacetylamino]-propionic acid methyl ester} fungicide at 0.11 g a.i. kg^{-1} seed before seeding each year.

Levels of N were 0 and 35 kg ha^{-1} surface-applied as granular ammonium nitrate (340 g N kg^{-1} material) using a granular fertilizer applicator on 7 June 1999, 15 May 2000, and 11 Apr. 2001. These applications were made within 14 d after emergence and before stage V2 and preceded all postemergent herbicide applications. Rainfall of >2 cm occurred 19, 5, and 1 d after N application in 1999, 2000, and 2001, respectively. Costs for the N and its application were \$38.20 ha^{-1}, \$41.40 ha^{-1}, and \$48.96 ha^{-1} in 1999, 2000, and 2001, respectively.

Weed management systems each year were (i) pre-emergent broadleaf followed by postemergent broadleaf and grass weed management using nonglyphosate herbicides applied to both GR and non-GR cultivars (PRE + POST) and (ii) postemergent broadleaf and grass weed management using glyphosate on GR cultivars and nonglyphosate herbicides on non-GR cultivars (POST). Within each WMS, use of herbicides and their combinations (Table 1) was dictated by expected weed populations (PRE) or actual populations (POST). Expert opinion during the growing season was used to determine when weed populations within each WMS were sufficient to justify application of postemergent herbicides and what herbicides to use. The PRE + POST WMS for GR cultivars received nonglyphosate herbicides applied postemergence to determine the effect of N application on GR cultivars that had no glyphosate applied to them. Two applications of glyphosate applied sequentially to GR cultivars in the POST treatment is supported by results from previous research (Gonzini et al., 1999; Wait et al., 1999; Payne and Oliver, 2000; Swanton et al., 2000). The objective in each WMS was to use the rates of glyphosate or nonglyphosate herbicides most likely to minimize weed competition within the constraints of each individual WMS each year.

Herbicides were broadcast-applied each year at labeled rates with recommended adjuvants and in recommended tank mixes (Table 1). Pre-emergent herbicides were applied immediately after planting, and rainfall of at least 13 mm occurred within 10 d of each application. Pre-emergent herbicides and postemergent nonglyphosate broadleaf herbicides were applied in 187 L ha^{-1} water, whereas postemergent grass herbicides and glyphosate were applied in 94 L ha^{-1} water per manufacturers' recommendations. Herbicides were applied using a canopied sprayer (Ginn et al., 1998a) for over-the-top applications (to prevent drift to adjacent plots of different treatments) or a directed sprayer (Ginn et al., 1998b) for applications underneath the developing soybean canopy. Application rates for each herbicide were premix of metribuzin [4-amino-6-(1,1-dimethylethyl)-3-(methylthio)-1,2,4-triazin-5 (4*H*)-one] at 450 g a.i. ha^{-1} plus chlorimuron ethyl {ethyl 2-[[[[(4-chloro-6-methoxypyrimidin-2-yl)amino]carbonyl] amino]sulfonyl]benzoate} at 75 g a.i. ha^{-1} applied pre-emergence, premix of 560 g a.i. ha^{-1} bentazon [3-(isopropyl)-1*H*-2,1,3-benzothiadiazin-4-(3*H*)-one 2,2-dioxide] and 280 g a.i. ha^{-1} acifluorfen {5-[2-chloro-4-(trifluoromethyl)phenox]-2-nitrobenzoate} applied postemergence, premix of 560 g a.i. ha^{-1} bentazon and 280 g a.i. ha^{-1} acifluorfen tank-mixed with 140 g a.i. ha^{-1} clethodim {(*E*)-2[1-[[(3-chloro-2-propenyl)oxy]imino]propyl]-5-[2-(ethylthio)propyl]-3-hydroxy-2-cyclohexen-1-one} and applied postemergence, sethoxydim {2-[1-(ethoxyimino) butyl]-5-[2-(ethylthio)propyl]-3-hydroxy-2-cyclohexen-1-one} at 213 g a.i. ha^{-1} applied postemergence, clethodim at 105 g a.i. ha^{-1} applied postemergence, tank mix of 2,4-DB [4-(2, 4-dichlorophenoxy)butyric acid, dimethylamine salt] at 224 g a.i. ha^{-1} plus linuron [3-(3, 4-dichlorophenyl)-1-methoxy-1-methylurea] at 560 g a.i. ha^{-1} applied postemergence as a directed spray underneath the soybean canopy, and glyphosate applied postemergence at 840 g a.i. ha^{-1}.

In the irrigated experiments, water was applied by the furrow method through gated pipe whenever soil water potential at the 30-cm depth, as measured by tensiometers, decreased to between −50 and −70 kPa. The effect of irrigation on yield of soybean in the midsouthern USA is well documented (Heatherly, 1999b), but irrigation environment can also affect infestation levels of some weed species (Heatherly et al., 1994, 2001, 2002a). Amounts of irrigation water applied and irrigation starting and ending dates each year were 360 mm applied between 7 July and 24 August in 1999, 355 mm applied between 28 June and 23 August in 2000, and 160 mm applied between 19 June and 24 July in 2001. Applied water traversed the area in furrows created by the tractor wheels during seeding on this soft clay soil. Irrigation amounts were determined by the degree of cracking in this shrink–swell soil (cracks when dry, swells when wet) because water applied to it through surface irrigation flows downward to the depth of cracking and rises to the surface as the cracks fill (Mitchell and van

Table 1. Herbicides used and their associated costs when applied in two weed management systems (WMS) to plantings of glyphosate-resistant (GR) and non-GR soybean cultivars at Stoneville, MS, 1999–2001.

WMS†	Cultivar	Herbicide‡	WMS expense§
			\$ ha^{-1}
		1999	
PRE + POST	non-GR	PRE metribuzin + chlorimuron; POST clethodim	89
POST	non-GR	Bentazon + acifluorfen + clethodim fb¶ 2,4-DB + linuron	102
PRE + POST	GR	PRE metribuzin + chlorimuron; POST clethodim	113
POST	GR	Glyphosate fb glyphosate	81
		2000	
PRE + POST	non-GR	PRE metribuzin + chlorimuron; POST bentazon + acifluorfen + clethodim	114
POST	non-GR	Bentazon + acifluorfen + clethodim fb bentazon + acifluorfen + clethodim	119
PRE + POST	GR	PRE metribuzin + chlorimuron; POST bentazon + acifluorfen + clethodim	135
POST	GR	Glyphosate fb glyphosate	72
		2001	
PRE + POST	non-GR	PRE metribuzin + chlorimuron; POST sethoxydim (nonirrigated only)	86 and 54#
POST	non-GR	Bentazon + acifluorfen fb bentazon + acifluorfen + clethodim (irrigated); bentazon + acifluorfen + clethodim fb bentazon + acifluorfen + clethodim (nonirrigated)	121 and 102
PRE + POST	GR	PRE metribuzin + chlorimuron; POST sethoxydim (nonirrigated only)	107 and 75
POST	GR	Glyphosate (irrigated and nonirrigated) fb glyphosate (nonirrigated)	65 and 43

† PRE + POST = pre-emergent broadleaf followed by postemergent broadleaf and grass weed management using nonglyphosate herbicides; POST = postemergent broadleaf and grass weed management using glyphosate on GR cultivars and nonglyphosate herbicides on non-GR cultivars.
‡ + indicates a premix and/or a tank mix.
§ Costs shown for GR cultivars include \$0.46 kg^{-1} (1999) and \$0.42 kg^{-1} (2000 and 2001) greater cost for their seed.
¶ fb = followed by.
# First number is for nonirrigated and second number for irrigated.

Table 2. Average daily maximum air temperatures (Max. T) and total rainfall amounts (Rain) for indicated months from 1999 through 2001, and 30-year normals at Stoneville, MS.

	1999		2000		2001		1964–1993 normals†	
Month	Max. T	Rain	Max. T	Rain	Max. T	Rain	Max. T	Rain
	°C	mm	°C	mm	°C	mm	°C	mm
Apr.	25.5	161	22.2	282	25.6	101	23.5	137
May	28.9	144	29.5	176	30.0	129	28.0	127
June	31.7	71	32.2	156	31.1	70	32.0	94
July	33.9	26	34.4	16	33.3	80	33.0	94
Aug.	35.6	6	36.7	0	32.8	215	32.5	58
Sept.	31.7	44	31.1	66	29.4	77	29.5	86

† Boykin et al., 1995.

Genuchten, 1993). Weather data presented in Table 2 were collected approximately 0.8 km from the experimental site by Delta Research and Extension Center personnel.

Weed control was determined after soybean leaf senescence to measure the season-long effect of WMSs that were intended to give complete weed control. Control of individual weed species was visually estimated based on weed density [scale of 0 (no weed control) to 100 (complete weed control)] similar to the method used by Reddy and Whiting (2000). Weed control data were subjected to analysis of variance using PROC MIXED (SAS Inst., 1998) to determine significance of main effects and any interactions among main effects. Treatment means were separated at the 5% level of probability using Fisher's Protected LSD test. Data were averaged across years because interactions involving year were not significant.

A field combine modified for small plots was used to harvest the four center rows of each plot on 10 (nonirrigated) and 23 (irrigated) Sept. 1999, 15 (nonirrigated) and 19 (irrigated) Sept. 2000, and 10 (irrigated) Sept. 2001. The nonirrigated study was not harvested in 2001 due to extreme weed reinfestation resulting from incomplete soybean canopy closure and the above-normal rainfall (245 mm) that occurred from 11 August through 3 September. Soybean seed from all plots were cleaned by the harvesting machine; thus, correction for foreign matter content in seed of any treatment combination was not necessary in any year. Harvested seed were weighed and adjusted to 130 g moisture kg^{-1} seed.

Estimates of total expenses and returns were developed for each annual cycle of each experimental unit using the Mississippi State Budget Generator (Spurlock and Laughlin, 1992). Total specified expenses were calculated using actual inputs for each treatment in each year of the experiment and included all operating expenses and machinery ownership costs but excluded charges for land, management, and general farm overhead, which were assumed to be the same for all treatment combinations. Machinery ownership costs for tractors, self-propelled harvesters, implements, sprayers, and the irrigation system were estimated by computing the annual capital recovery charge for each machine and applying its per-hectare rate to each field operation. Costs for machinery and operating expenses were based on prices paid by Mississippi farmers each year. Operating expenses included those for herbicides and adjuvants; seed; rollout vinyl pipe used in irrigation; labor; fuel, repair, and maintenance of machinery and irrigation systems; hauling harvested seed; and interest on operating capital. The price of seed for GR cultivars was \$0.46 kg^{-1} more than that for non-GR cultivars in 1999 and \$0.42 kg^{-1} more in 2000 and 2001; this extra cost was added to the weed management expense for GR cultivars. Weed management expenses after planting were calculated for each treatment and included charges for herbicides, surfactants, and application. All application charges included both operating expenses and ownership costs associated with tractors and sprayers. Irrigation expenses were based on a 65-ha furrow irrigation setup and included an annualized cost for the engine, well, pump, gearhead, generator, fuel tank and lines, and land leveling. The USDA loan rate of \$0.196 kg^{-1} soybean for Mississippi was used to calculate income from each experimental unit each year. Net return above total specified expenses was determined for each experimental unit each year.

Analysis of variance [PROC MIXED (SAS Inst., 1996)] was used to evaluate the significance of treatment effects on seed yield and net return separately for nonirrigated and irrigated experiments. Analyses across years treated year as a fixed effect to determine interactions involving year. Analyses for individual years treated cultivar, WMS, and N level as fixed effects, and the replicate × cultivar error term was assigned as random in the PROC MIXED model. Mean separation was achieved with an $LSD_{0.05}$.

RESULTS AND DISCUSSION

Weather and Soybean Development

Thirty-year average monthly maximum air temperatures and total rainfall (Boykin et al., 1995) at Stoneville are presented in Table 2. These normal weather patterns are associated with low yields from nonirrigated plantings because they result in drought stress to soybean that normally is in reproductive development from late June through early August (Heatherly, 1999b).

During this research, all years experienced undesirable weather at some time (Table 2). In 1999, average monthly maximum temperatures during April through June were near normal. High temperatures in conjunction with little rainfall in July and August resulted in severe stress for all cultivars in the nonirrigated environment. This stress was exacerbated by the relatively late planting date of 17 May in 1999 and the beginning bloom through full seed period occurring from late June through late August. In 2000, average monthly maximum temperatures from April through June were near normal while July and August temperatures were above normal. Rainfall in July and August of 2000 was only 16 mm. The beginning bloom through full seed period occurred from early June through mid-August. Again, these conditions resulted in severe stress for cultivars in the nonirrigated environment. In 2001, average monthly maximum temperatures were near normal in all months of the growing season. August 2001 rainfall was above normal and a record for the month. The beginning bloom through full seed period occurred from early May through late July. The low rainfall amounts in July and August of 1999 and 2000 resulted in greater irrigation amounts being applied in those years than in 2001.

Table 3. Percentage control of browntop millet (PANRA†), barnyardgrass (ECHCG), johnsongrass (SORHA), pitted morningglory (IPOLA), prickly sida (SIDSP), and hyssop spurge (EPHHS) at time of soybean harvest in glyphosate-resistant (GR) and non-GR soybean cultivars grown under two weed management systems (WMS‡) with and without early-season N (0 and 35 kg N ha^{-1}) in nonirrigated and irrigated environments at Stoneville, MS, 1999–2001§.

	Nonirrigated						Irrigated					
Factor	PANRA	ECHCG	SORHA	IPOLA	SIDSP	EPHHS	PANRA	ECHCG	SORHA	IPOLA	SIDSP	EPHHS
	%											
Year												
1999	100	100	97	95	100	100	100	100	99	92	99	100
2000	100	100	93	99	100	100	95	100	99	94	97	99
2001	–	–	–	–	–	–	82	98	92	81	92	99
$LSD_{0.05}$	NS	NS	NS	NS	NS	NS	7	1	4	11	2	NS
Cultivar												
non-GR	100	100	89	94	100	99	96	99	96	86	97	98
GR	100	100	98	99	100	100	85	99	96	89	95	100
GR	100	100	98	100	100	100	95	99	99	93	97	100
$LSD_{0.05}$	NS	NS	5	NS	NS	NS	8	NS	NS	NS	NS	NS
WMS												
PRE + POST	100	100	95	96	99	99	89	99	95	89	97	100
POST	100	100	95	99	100	100	95	99	98	90	96	99
$LSD_{0.05}$	NS	NS	NS	NS	NS	NS	3	NS	NS	NS	NS	NS
N rate												
0	100	100	94	97	100	100	92	99	96	92	96	99
35	100	100	95	98	100	100	93	99	98	87	96	100
$LSD_{0.05}$	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

† Weed Science Society of America–approved computer code (WSSA, 1984).
‡ PRE + POST = pre-emergent broadleaf followed by postemergent broadleaf and grass weed management using non-glyphosate herbicides; POST = postemergent broadleaf and grass weed management using glyphosate on GR cultivars and non-glyphosate herbicides on non-GR cultivars.
§ Weed control data for nonirrigated are average of 1999 and 2000; for irrigated, data are average of 1999, 2000, and 2001.

Weed Management Expense and Weed Control

Weed management costs for GR cultivars were always less with POST (only glyphosate used) than with PRE + POST (nonglyphosate herbicides used) (Table 1). For non-GR cultivars, PRE + POST was cheaper than POST in 1999 and 2001 while costs of the two were similar in 2000. Costs for PRE + POST applied to GR cultivars were greater than for PRE + POST applied to non-GR cultivars because of the greater cost for seed of GR cultivars. Costs for POST applied to GR cultivars were less than for POST applied to non-GR cultivars. This cheaper weed management with postemergent glyphosate compared with non-glyphosate postemergent herbicides over the course of this study agrees with results of Nelson and Renner (1999) and Heatherly et al. (2002a, 2002b). Over the 3 yr of this study, POST for GR cultivars cost the least, and PRE + POST for GR cultivars cost the most.

All WMSs provided excellent weed control at the end of the weed control period (immediately before irrigation initiation). In the nonirrigated environment, control of predominant weed species {barnyardgrass [*Echinochloa crus-galli* (L.) Beauv.], browntop millet [*Brachiaria ramosa* (L.) Stapf], hyssop spurge (*Euphorbia hyssopifolia* L.), johnsongrass [*Sorghum halepense* (L.) Pers.], pitted morningglory (*Ipomoea lacunosa* L.), and prickly sida (*Sida spinosa* L.)} at harvest ranged from 93 to 100% in 1999 and 2000, with no significant differences between years (Table 3). Control of these species averaged across years was ≥94% regardless of cultivar, WMS, and N level, with one exception: Small but significant differences in johnsongrass control among cultivars occurred, but control was at least 89% in all cultivars. The POST WMS was as effective in controlling weeds as the PRE + POST WMS. Application of early-season N (35 kg ha^{-1}) had no effect on weed control in the nonirrigated environment.

In the irrigated environment, use of both PRE + POST and POST WMSs in both non-GR and GR cultivars provided effective control of weeds. Control of the predominant weed species at harvest ranged from 92 to 100% among years (Table 3), with one exception: In 2001, browntop millet control was 82%, and pitted morningglory control was 81%. This reduced control was attributed to the earlier-opening canopy resulting from the early-April planting date in 2001 in conjunction with the August weather that provided a favorable environment for weed emergence and establishment. Among cultivars, WMSs, and N levels, differences in control of predominant weed species were not significant, with two exceptions: Small differences in control of browntop millet among cultivars and between WMSs were significant. The difference among cultivars was not associated with any measured trait or observed occurrence. Average control in the PRE + POST WMS (89%) was less than the 95% control in the POST WMS.

Soybean Seed Yield and Net Return

Nonirrigated

All yields were extremely low (average 730 and 1185 kg ha^{-1} in 1999 and 2000, respectively) as a result of drought stress each year (Table 4), and all net returns were negative (Table 5). Soybean seed yield was not significantly affected by N level or WMS in either year (Table 4). In both years, a GR cultivar produced the greatest yield. Use of 35 kg N ha^{-1} resulted in smaller average net returns in both years as a result of the additional cost with no concomitant increase in yield (Table 5). The cultivar × WMS interaction was significant for net return in both years. A GR cultivar pro-

Table 4. Seed yield of glyphosate-resistant (GR) and non-GR soybean cultivars (CULT) grown in nonirrigated and irrigated environments under two weed management systems (WMS) with and without early-season N [N rate (NRATE) of 0 and 35 kg N ha^{-1}] at Stoneville, MS, 1999–2001.

	Nonirrigated							Irrigated						
	WMS†							WMS						
	PRE + POST			POST				PRE + POST			POST			
	NRATE			NRATE				NRATE			NRATE			
CULT	0	35	Avg.	0	35	Avg.	CULT Avg.	0	35	Avg.	0	35	Avg.	CULT Avg.
	kg ha^{-1}													
							1999							
AP 4880 (non-GR)	680	670	675	605	685	645	660	3850	3755	3805	3680	3725	3705	3755
DP 4750 (GR)	735	790	760	715	715	715	740	3300	3330	3315	3435	3305	3370	3345
SG 468 (GR)	790	815	800	790	780	785	795	3600	3550	3575	3545	3525	3535	3555
Avg.	735	760	745	705	725	715	730	3585	3545	3565	3555	3520	3535	3550
$LSD_{0.05}$‡	CULT = 70; WMS = NS§; NRATE = NS							CULT = 120; WMS = NS; NRATE = NS						
							2000							
AP 4882 (non-GR)	1245	1230	1240	1125	1190	1160	1200	4255	4225	4240	4080	4120	4100	4170
DP 4690 (GR)	885	905	895	880	895	890	890	3550	3680	3615	4040	4025	4030	3825
AG 4702 (GR)	1445	1455	1450	1435	1550	1495	1470	3650	3880	3765	4040	4200	4120	3940
Avg.	1190	1195	1195	1145	1210	1180	1185	3820	3930	3875	4050	4115	4085	3980
$LSD_{0.05}$‡	CULT = 85; WMS = NS; NRATE = NS							CULT = 105; WMS = 90; NRATE = NS; CULT × WMS = 150						
							2001							
AP 4882 (non-GR)								3305	3255	3280	3525	3465	3495	3385
DP 4690 (GR)								3105	3295	3200	3300	2845	3075	3135
AG 4702 (GR)								2810	3095	2955	2900	3040	2970	2960
Avg.								3075	3215	3145	3240	3115	3180	3160
$LSD_{0.05}$‡								CULT = 325; WMS = NS; NRATE = NS; WMS × NRATE = 180						

† PRE + POST = pre-emergent broadleaf followed by postemergent broadleaf and grass weed management using non-glyphosate herbicides; POST = postemergent broadleaf and grass weed management using glyphosate on GR cultivars and non-glyphosate herbicides on non-GR cultivars.
‡ CULT = LSD for CULT mean separation; WMS = LSD for WMS separation; CULT × WMS = LSD for CULT × WMS interaction; WMS × NRATE = LSD for WMS × NRATE interaction.
§ NS = no significant effect.

duced a greater net return than the non-GR cultivar within each WMS. Within cultivar, the PRE + POST WMS resulted in more net return for the non-GR cultivar each year while the opposite was true for the GR cultivars. Again, all yields were low and all net returns negative. It is obvious from these results that any surmised yield reduction from use of glyphosate on GR soybean in the field will not occur when drought stress is severe.

Irrigated

Soybean seed yield was not significantly affected by N level in any year, with difference in average yields from the 0 and 35 kg ha^{-1} N treatments ranging from 0 to 85 kg ha^{-1} across the 3 yr (Table 4). The effect of the interaction between cultivar and N level on seed yield was never significant, indicating that added N had no more effect on GR cultivars than on non-GR cultivars in any year. In 1999, the non-GR cultivar produced the greatest yield, and WMS did not significantly affect yield. In 2000, the cultivar × WMS interaction significantly affected yield. In the PRE + POST WMS, the non-GR cultivar produced the greatest yield, whereas yields of all cultivars where POST was used were statistically similar. The POST WMS produced the greater yield when GR cultivars were used, whereas PRE + POST and POST WMSs produced similar yields with the non-GR cultivar. In 2001, the non-GR cultivar significantly outyielded the GR cultivar AG 4702, but its yield was statistically similar to that of GR DP 4690. The WMS × N level interaction significantly affected yield. When zero N was used, the POST WMS resulted in a greater yield; when 35 kg ha^{-1} N was used, yields from PRE + POST and POST were not significantly different.

Use of 35 kg N ha^{-1} resulted in smaller average net returns in all years as a result of the additional cost, with no significant yield increase sufficient to offset cost of N (Table 5). The cultivar × WMS interaction was significant for net return in 1999 and 2000. Use of the non-GR cultivar resulted in greater net returns when PRE + POST was used than did use of GR cultivars. When POST was used, use of a GR cultivar resulted in net return that was similar to or greater than that from the non-GR cultivar. Within cultivar, the PRE + POST WMS resulted in greater net return from the non-GR cultivar each year while the opposite was true for the GR cultivars. In 2001, use of the non-GR cultivar resulted in a greater net return than that from use of AG 4702. The WMS × N level interaction was significant for net return in 2001. When the PRE + POST WMS was used, N level had no significant effect; when POST was used, using 35 kg ha^{-1} N resulted in smaller net return. Net return from use of POST was greater only when the zero N level was used.

SUMMARY AND CONCLUSIONS

Application of early-season N (35 kg ha^{-1}) to soybean resulted in more expense, no increase in yield, and

Table 5. Net return from glyphosate-resistant (GR) and non-GR soybean cultivars (CULT) grown in nonirrigated and irrigated environments under two weed management systems (WMS) with and without early-season N [N rate (NRATE) of 0 and 35 kg N ha^{-1}] at Stoneville, MS, 1999–2001.

	Nonirrigated							Irrigated						
	WMS†							WMS						
	PRE + POST			POST				PRE + POST			POST			
	NRATE			NRATE				NRATE			NRATE			
CULT	0	35	Avg.	0	35	Avg.	CULT Avg.	0	35	Avg.	0	35	Avg.	CULT Avg.
	$ ha^{-1}													
1999														
AP 4880 (non-GR)	−193	−236	−214	−221	−246	−233	−224	274	216	245	228	197	213	229
DP 4750 (GR)	−192	−222	−207	−178	−219	−198	−203	160	125	142	204	138	171	157
SG 468 (GR)	−180	−216	−198	−163	−205	−184	−191	219	168	193	225	181	203	198
Avg.	−188	−224	−206	−187	−223	−205	−206	217	170	194	219	172	196	195
$LSD_{0.05}$‡	CULT = 14; WMS = NS§ NRATE = 7; CULT × WMS = 15/13¶							CULT = 23; WMS = NS; NRATE = 19; CULT × WMS = 33						
2000														
AP 4882 (non-GR)	−112	−159	−136	−140	−172	−156	−146	307	256	282	268	232	250	266
DP 4690 (GR)	−200	−241	−221	−136	−177	−156	−189	153	133	143	312	264	288	216
AG 4702 (GR)	−95	−136	−115	−30	−52	−41	−78	172	171	171	312	298	305	238
Avg.	−136	−179	−157	−102	−134	−118	−138	210	187	199	297	265	281	240
$LSD_{0.05}$‡	CULT = 16; WMS = 13; NRATE = 13; CULT × WMS = 23							CULT = 20; WMS = 17; NRATE = 17; CULT × WMS = 29						
2001														
AP 4882 (non-GR)								266	206	236	260	198	229	233
DP 4690 (GR)								200	185	192	273	135	204	198
AG 4702 (GR)								147	150	149	200	175	188	168
Avg.								205	180	192	244	169	207	200
$LSD_{0.05}$‡								CULT = 62; WMS = NS; NRATE = 24; WMS × NRATE = 34						

† PRE + POST = pre-emergent broadleaf followed by postemergent broadleaf and grass weed management using non-glyphosate herbicides; POST = postemergent broadleaf and grass weed management using glyphosate on GR cultivars and non-glyphosate herbicides on non-GR cultivars.
‡ CULT = LSD for cultivar mean separation; WMS = LSD for WMS separation; CULT × WMS = LSD for CULT × WMS interaction; WMS × NRATE = LSD for WMS × NRATE interaction.
§ NS = no significant effect.
¶ Where two numbers appear for interactions, the first is LSD for comparing CULT means within a WMS level, and the second is LSD for comparing WMS means within CULT.

smaller net returns for both GR and non-GR cultivars grown in nonirrigated and irrigated environments regardless of whether nonglyphosate or glyphosate herbicides were used. Application of early-season N had no effect on weed control in either nonirrigated or irrigated environments. The POST weed management program was as effective in controlling weeds as the PRE + POST weed management in both non-GR and GR soybean cultivars. Other researchers have reported that pre-emergent herbicides were not necessary to supplement POST weed management programs in GR soybean for control of common weeds (Gonzini et al., 1999; Culpepper et al., 2000; Reddy and Whiting, 2000; Heatherly et al., 2002b). In the nonirrigated environment, GR cultivars produced slightly greater yields than non-GR cultivars, but the opposite was true in the irrigated environment.

In the nonirrigated environment, all net returns were negative because of extremely low yields resulting from extreme drought stress, and use of early-season N reduced net return even more. In the irrigated environment, non-GR cultivars generally produced greater yield and net return than GR cultivars. Net returns from non-GR cultivars were greater with PRE + POST than with POST WMS in 2 of the 3 yr while net returns from GR cultivars were greater with POST than with PRE + POST in all years. Neither glyphosate nor early-season N significantly affected yield of GR cultivars in the POST WMS that received glyphosate compared with nonglyphosate postemergent herbicides in both irrigated and nonirrigated environments. This contrasts with results from a 1-yr field study conducted by King et al. (2001), who inferred from this study that glyphosate tends to decrease seed yields of GR cultivars grown with limited soil water.

In the present study, early-season N application to soybean did not benefit yield of either GR or non-GR cultivars and resulted in smaller net returns. These results also indicate that using PRE + POST compared to POST-only weed management with GR cultivars will result in smaller net returns because of the increased cost incurred from using pre-emergent herbicides in conjunction with greater cost for seed of GR cultivars.

ACKNOWLEDGMENTS

The authors appreciate the technical assistance provided by Sandra Mosley, John Black, and Albert Tidwell; resources provided by the Delta Research and Extension Center; and supplemental funding provided by the United Soybean Board and the Mississippi Soybean Promotion Board.

REFERENCES

Amrhein, J., J. Schab, and H.C. Steinrücken. 1980. The mode of action of the herbicide glyphosate. Naturwissenschaften 67:356–357.

Boykin, D.L., R.R. Carle, C.D. Ranney, and R. Shanklin. 1995. Weather data summary for 1964–1993, Stoneville, MS. MAFES Tech. Bull. 201. Mississippi Agric. and Forestry Exp. Stn., Mississippi State Univ., Mississippi State.

Buhler, D.D., R.P. King, S.M. Swinton, J.L. Gunsolus, and F. Forcella. 1997. Field evaluation of a bioeconomic model for weed management in soybean (*Glycine max*). Weed Sci. 45:158–165.

Culpepper, A.S., A.C. York, R.B. Batts, and K.M. Jennings. 2000. Weed management in glufosinate- and glyphosate-resistant soybean (*Glycine max*). Weed Technol. 14:77–88.

Elmore, R.W., F.W. Roeth, R. Klein, S.Z. Knezevic, A. Martin, L. Nelson, and C.A. Shapiro. 2001. Glyphosate-resistant soybean cultivar response to glyphosate. Agron. J. 93:404–407.

Ferguson, R.B., E.J. Penas, and W.B. Stevens. 2000. Soybean. p. 121–125. *In* R.B. Ferguson and K.M. DeGroot (ed.) Nutrient management for agronomic crops in Nebraska. EC-01–155. Univ. of Nebraska Coop. Ext. Serv., Lincoln.

Gibson, A.H., and J.E. Harper. 1985. Nitrate effect on nodulation of soybean by *Bradyrhuzobium japonicum*. Crop Sci. 25:497–501.

Ginn, L.H., E.R. Adams, L.G. Heatherly, and R.A. Wesley. 1998a. A canopied sprayer for accurate application of herbicides. Agron. J. 90:109–112.

Ginn, L.H., L.G. Heatherly, E.R. Adams, and R.A. Wesley. 1998b. A sprayer for under-canopy application of herbicide sprays. J. Prod. Agric. 11:196–199.

Gonzini, L.C., S.E. Hart, and L.M. Wax. 1999. Herbicide combinations for weed management in glyphosate-resistant soybean (*Glycine max*). Weed Technol. 13:354–360.

Heatherly, L.G. 1999a. The stale seedbed planting system. p. 93–102. *In* L.G. Heatherly and H.F. Hodges (ed.) Soybean production in the Mid-south. CRC Press, Boca Raton, FL.

Heatherly, L.G. 1999b. Soybean irrigation. p. 119–142. *In* L.G. Heatherly and H.F. Hodges (ed.) Soybean production in the Mid-south. CRC Press, Boca Raton, FL.

Heatherly, L.G., and C.D. Elmore. 1983. Response of soybeans to planting in untilled, weedy seedbed on clay soil. Weed Sci. 31:93–99.

Heatherly, L.G., C.D. Elmore, and S.R. Spurlock. 1994. Effect of irrigation and weed control treatment on yield and net return from soybean (*Glycine max*). Weed Technol. 8:69–76.

Heatherly, L.G., C.D. Elmore, and S.R. Spurlock. 2001. Row width and weed management systems for conventional soybean plantings in the midsouthern USA. Agron. J. 93:1210–1220.

Heatherly, L.G., and S.R. Spurlock. 1999. Yield and economics of traditional and early soybean production system (ESPS) seedings in the midsouthern United States. Field Crops Res. 63:35–45.

Heatherly, L.G., S.R. Spurlock, and C.D. Elmore. 2002a. Row width and weed management systems for early soybean production system plantings in the midsouthern USA. Agron. J. 94:1172–1180.

Heatherly, L.G., C.D. Elmore, and S.R. Spurlock. 2002b. Weed management systems for conventional and glyphosate-resistant soybean with and without irrigation. Agron. J. 94:1419–1428.

Hoeft, R.G., E.D. Nafziger, R.R. Johnson, and S.R. Aldrich. 2000. Modern corn and soybean production. 1st ed. MCSP Publ., Champaign, IL.

Johnson, R.R. 1987. Crop management. p. 355–390. *In* J.R. Wilcox (ed.) Soybeans: Improvement, production, and uses. 2nd ed. Agron. Monogr. 16. ASA, CSSA, and SSSA, Madison, WI.

Johnson, W.G., J.A. Kendig, R.E. Massey, M.S. DeFelice, and C.D. Becker. 1997. Weed control and economic returns with postemergence herbicides in narrow-row soybeans. Weed Technol. 11:453–459.

King, C.A., L.C. Purcell, and E.D. Vories. 2001. Plant growth and nitrogenase activity of glyphosate-tolerant soybean in response to foliar glyphosate applications. Agron. J. 93:179–186.

Mitchell, A.R., and M.Th. van Genuchten. 1993. Flood irrigation of a cracked soil. Soil Sci. Soc. Am. J. 57:490–497.

Nelson, K.A., and K.A. Renner. 1999. Weed management in wide- and narrow-row glyphosate resistant soybean. J. Prod. Agric. 12:460–465.

Padgette, S.R., N.B. Taylor, D.L. Nida, M.R. Bailey, J. MacDonald, L.R. Holden, and R.L. Fuchs. 1996. The composition of glyphosate-tolerant soybean seeds is equivalent to that of conventional soybeans. J. Nutr. 126:702–716.

Payne, S.A., and L.R. Oliver. 2000. Weed control programs in drilled glyphosate-resistant soybean. Weed Technol. 14:413–422.

Pettry, D.E., and R.E. Switzer. 1996. Sharkey soils in Mississippi. Bull. 1057. Mississippi Agric. and Forestry Exp. Stn., Mississippi State Univ., Mississippi State.

Reddy, K.N. 2001. Glyphosate-resistant soybean as a weed management tool: Opportunities and challenges. Weed Biol. Manage. 1: 193–202.

Reddy, K.N., L.G. Heatherly, and A. Blaine. 1999. Weed management. p. 171–195. *In* L. G. Heatherly and H. F. Hodges (ed.) Soybean production in the Mid-south. CRC Press, Boca Raton, FL.

Reddy, K.N., R.E. Hoagland, and R.M. Zablotowicz. 2000. Effect of glyphosate on growth, chlorophyll, and nodulation in glyphosate-resistant and susceptible soybean (*Glycine max*) varieties. J. New Seeds 2:37–52.

Reddy, K.N., and K. Whiting. 2000. Weed control and economic comparisons of glyphosate-resistant, sulfonylurea-tolerant, and conventional soybean (*Glycine max*) systems. Weed Technol. 14: 204–211.

SAS Institute. 1996. SAS system for mixed models. SAS Inst., Cary, NC.

SAS Institute. 1998. Software version 7.00. SAS Inst., Cary, NC.

Spurlock, S.R., and D.H. Laughlin. 1992. Mississippi state budget generator user's guide version 3.0. Agric. Econ. Tech. Publ. 88. Mississippi State Univ., Mississippi State.

Swanton, C.J., A. Shrestha, K. Chandler, and W. Deen. 2000. An economic assessment of weed control strategies in no-till glyphosate-resistant soybean (*Glycine max*). Weed Technol. 14:755–763.

Varco, J.J. 1999. Nutrition and fertility requirements. p. 53–70. *In* L.G. Heatherly and H. F. Hodges (ed.) Soybean production in the Mid-south. CRC Press, Boca Raton, FL.

Wait, J.D., W.G. Johnson, and R.E. Massey. 1999. Weed management with reduced rates of glyphosate in no-till, narrow-row, glyphosate-resistant soybean (*Glycine max*). Weed Technol. 13:478–483.

Webster, E.P., K.J. Bryant, and L.D. Earnest. 1999. Weed control economics in nontransgenic and glyphosate-resistant soybean. Weed Technol. 13:586–593.

Whitney, D.A. 1997. Fertilization. p. 11–13. *In* Soybean production handbook. C-449. Kansas State Univ. Coop. Ext. Serv., Manhattan.

Williams, B. 1999. Economics of soybean production in Mississippi. p. 1–17. *In* L.G. Heatherly and H.F. Hodges (ed.) Soybean production in the Mid-south. CRC Press, Boca Raton, FL.

[WSSA] Weed Science Society of America. 1984. Composite list of weeds. Vol. 32. Suppl. 2. WSSA, Lawrence, KS.