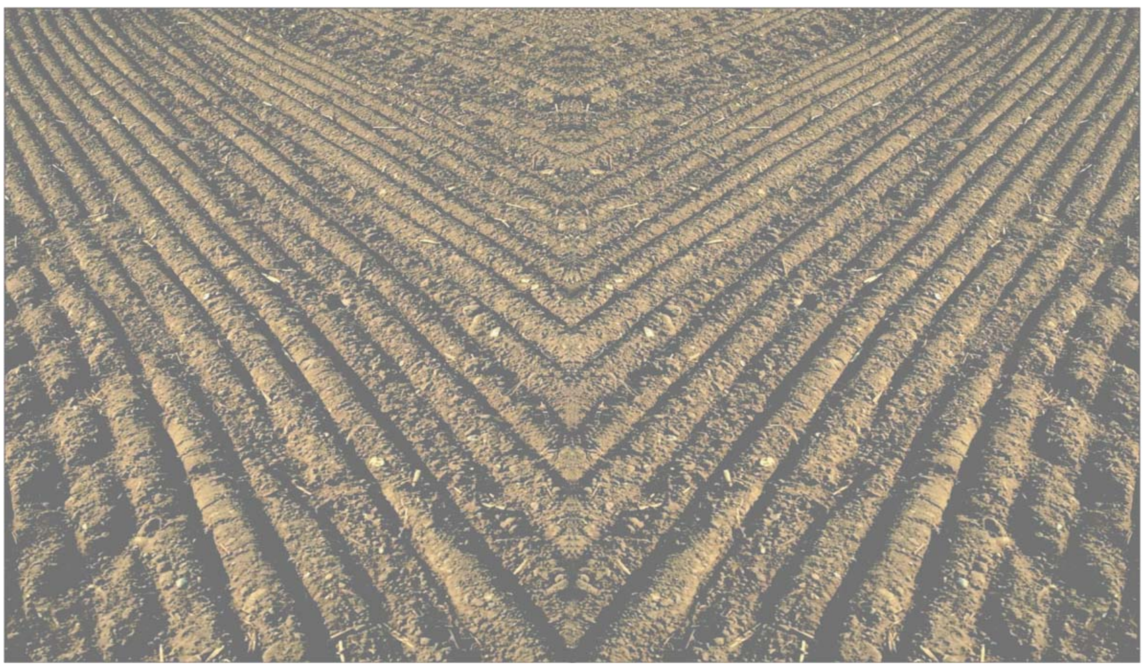
Troubled Times Amid Commercial Success for Roundup Ready Soybeans

Glyphosate Efficacy is Slipping and Unstable Transgene Expression Erodes Plant Defenses and Yields



Dr. Charles M. Benbrook
Northwest Science and Environmental Policy Center
Sandpoint Idaho

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Executive Summary

Roundup Ready soybeans have clearly been a great commercial success. Over 60 percent of soybeans in the United States this year will be planted to RR varieties, just five years after introduction in 1996.

Despite costing more, farmers have eagerly adopted Roundup Ready soybean technology because it greatly simplifies weed management. RR systems do so by allowing the farmer to spray a single broad-spectrum herbicide active ingredient – glyphosate (Roundup) – over the top of growing soybeans, killing most weeds but leaving genetically engineered Roundup Ready (RR) soybeans largely unharmed.

RR soybeans make it possible for farmers to avoid or cut back use of persistent, highly active low-dose herbicides, many of which can injure soybean plants and depress yields. A last and major advantage -- RR soybean-based weed management systems are forgiving. They provide farmers a wider window of opportunity to deal with problem weeds and extra chances to make up for delays in field operations or for an untimely rain that washes herbicides off weeds before they are absorbed. On some farms these advantages add up to slightly more bushels harvested per acre than when conventional soybean varieties were planted.

Still, Roundup Ready soybean systems are costly in more ways than one and some costs are rising.

Herbicide Use

RR soybeans clearly require more herbicides than conventional soybeans, despite claims to the contrary. This conclusion is firmly supported by unbiased field-level comparisons of the total pounds of herbicide active ingredient applied on an average acre of RR soybeans in contrast to conventional soybeans. Part I presents such field-level data for 1998, drawing on official U.S. Department of Agriculture pesticide use data. It also explains how Monsanto has manipulated comparative data on RR and conventional soybean herbicide use in ways that fall between misleading and dishonest.

Rates of application per acre are the key variable that explains why RR soybeans require more herbicides than other varieties. More than a dozen soybean herbicides are applied at an average rate of less than 0.1 pound active ingredient per acre. Roundup, on the other hand, is usually applied on soybeans at about 0.75 pounds per acre in a single spray and most acres are now treated more than once. According to Monsanto, about one-quarter of RR soybean acres will be treated three times with glyphosate, in systems requiring well over 1.5 pounds of herbicides.

Total herbicide use on RR soybeans in 1998 was 30 percent or more greater on average than on conventional varieties in six states, including Iowa where about one-sixth of the nation's soybeans are grown. RR soybean herbicide use was 10 percent or more great in three more states. Use on RR soybeans was modestly lower in five states. Use was significantly lower only in Michigan, where less than 3 percent of the nation's soybeans are grown.

Actual per acre herbicide use data in 1998, as measured field-by-field by USDA, was used to assess the distribution of herbicide use along a continuum from the most herbicide dependent systems to the least dependent. On the 30 percent of soybean fields managed with the most herbicide-intensive systems under conventional/conservation tillage, including essentially all RR soybeans planted under conventional/conservation tillage, at least 1.7 times more herbicide was applied per acre compared to the 30 percent of soybean acres that required the least amount of herbicides – fields where farmers relied mostly on the low-dose sulfonylurea and imidazolinone herbicides and which were clearly ***not*** planted to RR soybeans.

When total herbicide use per acre is compared at the tail ends of the distribution (i.e., the top10 percent of acres versus the bottom 10 percent), the difference is much more striking, especially on fields under conventional/conservation tillage. The most heavily treated fields, most of which were planted to RR soybeans, required at least 34 times more herbicide than fields planted to non-RR varieties at the low-end of the distribution.

Under no-till the most heavily treated 30 percent of fields required twice the herbicide as the 30 percent of acres at the low-end of the distribution. Most RR fields fall in this top 30 percent and essentially none are in the lower 30 percent.

Looking ahead to crop year 2001, it is likely that the average acre of RR soybeans will be treated with about 0.5 pounds more herbicide active ingredient than conventional soybeans. As a result over 20 million more pounds of herbicides will be applied this crop year. In addition, the difference between herbicide use on RR and conventional soybean varieties is clearly growing and for several reasons.

Intense herbicide price competition, triggered by the commercial success of RR soybeans, has reduced the average cost per acre treated with most of today's popular herbicides by close to 50 percent since the introduction of RR soybeans. In response farmers are applying more active ingredients at generally higher rates. But heightened reliance on herbicides, especially Roundup, has accelerated the shift in weed species in ways that is undermining the efficacy of Roundup and requiring farmers to add new products to their control programs. These trends increase the risk of resistance and will ultimately lead to less reliable and more costly systems.

RR Soybean Yield Drag

There is voluminous and clear evidence that RR soybean cultivars produce 5 percent to 10 percent fewer bushels per acre in contrast to otherwise identical varieties grown under comparable field conditions. Recent evidence of the magnitude of the Roundup Ready yield drag is summarized in part II, along with the results of studies that have begun to isolate the genetic basis of the RR yield drag.

The yield drag between the top five leading RR varieties in a maturity group in contrast to the top five conventional varieties in the same maturity group is assessed in three to four locations in each of three states. In Illinois the top-five yield drag averaged 2.3 percent. In Minnesota the top-five yield drag averaged 6.1 percent and in Nebraska, 2.9 percent. A special study by a team at the University of Nebraska study estimated that the genetic differences between RR varieties and otherwise similar varieties, when grown under comparable conditions, is about 6 percent.

In a January 2001 story on corn and soybean seed selection, *Farm Journal* magazine shared with its readers the results of independent soybean yield trials in three states conducted under conditions designed to match those on commercial farms. In Indiana, the top RR variety offered by three seed companies yielded, on average, 15.5 percent fewer bushels than the top conventional variety from the same company. In Illinois plots, however, the top RR to top conventional yield drag across eight companies was less than 1 percent. In Iowa trials, the RR yield drag was just under 19 percent across 17 companies.

New Science Traces the RR Yield Drag to Its Roots

Soybean yields have been increasingly erratic across the Cornbelt in recent years. Many fields have suffered yield losses far greater than expected given the magnitude of the RR yield drag. The search is on for answers and recently some have emerged.

University of Arkansas scientists have shown that root development, nodulation and nitrogen fixation is impaired in some RR soybean varieties and that the effects are worse under conditions of drought stress or in relatively infertile fields. This problem arises because the bacterial symbiont responsible for nitrogen fixation in soybeans, *Bradyrhizobium japonicum*, is very sensitive to both Roundup and drought. The combination of Roundup and drought is clearly not unusual across the 65-70 million acres planted to soybeans each year.

Soybean compositional studies carried out by Monsanto have documented a modest but statistically significant decrease in the levels of two key aromatic amino acids, phenylalanine and tyrosine, in harvested soybeans. Phenylalanine serves as a sort of "master control switch" for a range of soybean plant defense responses that must unfold in a timely and properly targeted way when the plant is attacked by pests or stressed by drought or other abiotic factors.

New evidence suggests that levels of these regulatory proteins are being depressed more substantially for a few days to a week or more after Roundup is sprayed on fields planted to RR soybeans. In years or regions with modest pest pressure and where moisture supplies and growing conditions are optimal, RR soybean plants restore phenylalanine and other regulatory proteins to normal levels quickly and suffer no long-term consequences. But where growing conditions are less than optimal, even temporary depression of RR soybean plant defense mechanisms can give pathogens a chance to multiple largely unchecked and initiate infections. This head start forces the plant to invest energy over an extended period of time in repairing and containing the damage. While regulatory protein levels in the harvested soybeans from such fields often return to, or nearly to normal levels, the temporal diversion of plant energy extracts an essentially irreversible tax on yields.

Troubled Times will Trigger Changes in Soybean Weed Management

As new soybean weed control options emerge and are integrated into multitactic soybean weed management systems, fewer farmers will be willing to accept the trade-offs and costs now inherent in selection of a RR variety. There are two major factors on the plus side of RR soybean trade-offs -- weed management is simplified and soybean crop injury is avoided. But troubled times lie ahead for RR soybeans because the efficacy of glyphosate is clearly slipping in managing weeds and because unanticipated yield penalties are surfacing in some RR fields, traced to how genetic engineers have modified soybean plants to make them Roundup Ready. As farmers begin to understand the practical implications of what researchers have recently discovered, interest will grow in other less costly ways to manage soybean weeds.

The U.S. agricultural biotechnology industry and the farm community should heed three important lessons in the rapid adoption and now shaky future of RR soybeans.

1. Any biotechnology that heightens reliance on a single pest management tool, and especially a single herbicide, is headed for trouble.

Herbicide-tolerant crop technologies are designed to allow farmers to increase their reliance on herbicides. It is therefore not surprising that RR soybeans require more herbicides than other weed management systems, especially those that incorporate "many little hammers" in combinations that change from year-to-year.

Spraying Roundup two or three times on a RR soybean field, often at steadily higher rates and sometimes followed the next crop season with two or three more applications on RR corn, has imposed on weed populations unprecedented levels of selection pressure, leading to shifts in weed species composition and resistance or lost sensitivity in other target weeds.

Roundup Ready soybean technology is, to a large extent, a victim of its own success. Excessive reliance on Roundup as the major, if not sole means of weed management unleashes basic evolutionary forces that farmers – and agribusiness – ignore at their peril.

2. Inserting transgenes into major plant metabolic pathways is a risky proposition that is likely to lead to unanticipated consequences, especially when plants are stressed by unusual weather, pests, or infertile or imbalanced soils.

When plants are stressed, transgene expression may be silenced or otherwise disrupted as a secondary consequence of the plant's normal physiological response to the source (or sources) of stress. Even modest and short-term depression in the production of key regulatory aromatic amino acids in RR soybean varieties can tip the competitive edge toward opportunistic pathogens.

Once pathogens gain a head start, the plant will have to invest energy in fighting them back and containing their spread. This diversion of energy sometimes extracts an irrevocable yield penalty, despite the fact that the plants and the harvested soybeans appear perfectly normal and "substantially equivalent" upon harvest at the end of the season.

3. The lack of independent research on the ecological, agronomic and plant defense consequences of RR soybeans, until well after regulatory approvals and widespread market penetration, blindsided regulators and has heightened the vulnerability of farmers.

It is remarkable that over 100 million acres of Roundup Ready soybeans were planted in America before publication in 2001 of the first university data documenting the sometimes-serious depression of nitrogen fixation in RR soybean fields.

Ignorance creates a false sense of security and sets the stage for trouble. The U.S. regulatory system is better at avoiding problems that dealing with them once a technology is entrenched, with profits and market share to defend. In the case of RR soybeans, the regulatory system's ability to ferret out risks and resolve uncertainties was, in effect, silenced because regulators had little to go on in formulating questions.

Moving On

Understanding should evolve quickly now that several independent research teams have started to publish results on the downsides of the RR soybean system. But the mechanisms leading to RR soybean yield losses are many, complex and highly variable. Scientists will struggle to just keep pace with soybean weed management changes and many problems will come and go before anyone understands fully where they came from and why.

New technologies in the future will have a better chance of sustaining a place in U.S. soybean weed management systems if the above three lessons are heeded. The fuller the soybean weed management toolkit, the easier time farmers will have in keeping their fields clean and yields up. In managing weeds, keeping a few steps ahead of Mother Nature is the ultimate measure of success, and a standard of performance that appears beyond the reach of today's RR soybean system.

I. Herbicides Applied to Conventional and Roundup Ready Soybeans

Herbicides have done the heavy lifting in soybean weed management systems since the early 1970s. Compared to corn, soybean plants do not produce nearly as much foliage, and hence soybean fields are more susceptible to high rates of soil erosion. For this reason, farmers have tried to minimize tillage in the years they are planting soybeans.

While good for the soil and for water quality, reduced tillage soybean systems are, in general, more reliant on herbicides in keeping weeds under control. (For a more detailed discussion of the evolution in weed management systems in the United States and impacts on herbicide use, see *Pest Management at the Crossroads* [Benbrook, et al., 1996]).

A. Historical Overview of Herbicide Use in Soybean Production

In the early to mid-1980s, most soybean herbicides were applied in combinations and tillage and cultivation still played a significant role in weed management systems on many farms. Combined herbicide rates typically fell between 0.75 to 1.5 pounds per acre. Many of the products that dominated soybean herbicide use in the 1980s are still popular today. They remain widely used because they still work reasonably well and are one-half or less the cost per acre treated relative to the newer, lower-dose products that started to hit the market in the mid-1980s. These older products include trifluralin, pendimethalin, 2,4-D, sethoxydim, and alachlor/metalochlor.

There is now a dizzying array of soybean herbicides on the market. Many are sold in combination products containing two or three active ingredients at rates designed to fit with today's popular tillage and planting systems. Most of the newest combination products have been introduced specifically to augment weed control in fields planted to Roundup varieties.

A detailed study of RR soybean production, herbicide use, and profitability in 1998 was carried out by the National Center for Food and Agricultural Policy, or NCFAP (Gianessi and Carpenter, 2000). The report, "Agricultural Biotechnology: Benefits of Transgenic Soybeans," provides a thorough discussion of historical soybean weed management and the aggregate impacts of RR soybeans. The authors analyzed aggregate USDA herbicide use data in soybeans and concluded that introduction of RR soybeans had little net effect on total herbicide use, measured in pounds applied per acre.

In the NCFAP report, the authors acknowledge they lacked access to detailed soybean field-by-field herbicide use data – the information any analyst would need to definitively assess differences in average per acre pounds of herbicides applied on RR planted fields in contrast to the average pounds applied to other fields. The original analytical results reported in this chapter are based on such field-by-field comparisons of herbicide use and required special tabulations of herbicide use by sample point (a field), drawing on the raw data files collected by USDA in its 1998 soybean agrichemical use survey.

RR Soybeans Trigger Herbicide Price War

While the NCFAP report does not address field-level differences in per acre herbicide use, it contains a wealth of other data and results. For example, it fully documents the reductions in herbicide prices triggered by the need for other companies to compete with the RR soybean system.

Dupont, the major manufacturer of the sulfonylurea herbicides, was the first to pull the plug on prices in an attempt to slow their loss of soybean herbicide market share. Prices of 42 herbicide products were cut (Reeves, 1997). In 1996, farmers paid $1,220.00 per pound of the very low-dose sulfonylurea herbicide chlorimuron (Classic), or about $15.00 per acre treated (Table 16, Gianessi and Carpenter, 2000). In 1997, Dupont slashed the price to $620.00 per pound, reducing the cost per acre treated at full rates to under $8.00 – about the average cost of an acre-treatment with Roundup. Dupont also cut the price of metribuzin (Sencor) from $40.00 per pound in 1995 to just over $26.70 now, a 33 percent decrease, bringing average per acre treatment costs down from $9.30 to $6.20.

Dupont's price reductions were widely covered in the farm press and widely emulated in the herbicide industry. The November 1997 issue of *Dealer Progress* included a story entitled "Caught in the Crossfire: Roundup Ready Soybeans Trigger a Herbicide Price War that could Wound Your Profits" (Reeve, 1997). It begins with the passage –

> "Roundup Ready soybeans have seized the hearts, minds and fields of U.S. farmers with the kind of speed that would make Norman Schwartzkopf proud."

American Cyanamid, the major manufacturer of the popular imidazolinone herbicides, underestimated the appeal of RR soybeans and lost major market share as a result. Unlike Dupont, American Cyanamid delayed an extra year before dropping the price of its flagship product – imazethapyr (Pursuit). This herbicide was the most widely used throughout the early 1990s. It was applied to 44 percent of soybean acres in 1995, the year before the introduction of RR soybeans. In crop year 1997, its market share had declined just 6 percent, but in the fall of 1997, the competitive threat posed by RR beans was clear to everyone in the industry (Gianessi and Carpenter, 2000).

In early 1998, American Cyanamid announced across-the-board soybean herbicide price reductions. The price per pound of imazethapyr dropped from $340.00 to $200.00, a 42 percent drop. The cost per acre treated fell from $13.60 in 1997 to $8.00, again very competitive with Roundup. Even so, imazethapyr's market share declined from 38 percent of acres treated in 1997 to just 17 percent in 1998.

In the late winter and spring of 1999, American Cyanamid cut prices, intensified advertising and offered all sorts of creative rebates and guarantees to try to slow its slipping share of the soybean herbicide market. In March, they issued a press release that began by asserting –

> “America’s farmers could experience yield losses up to $43 per acre when choosing Monsanto’s Roundup Ready soybean program.” American Cyanamid, 1999)

The huge and rapid erosion in Cyanamid’s soybean herbicide market share had a serious adverse impact on the parent company’s stock performance and was a major factor triggering the sale of the American Cyanamid agricultural chemical and seed division to the German-based company BASF in 2000.

Monsanto added to the downward pressure on herbicide prices in 1998 by reducing the price of Roundup from $18.00 per pound to $14.00, about a 22 percent price drop. This year Roundup is selling for about $10.00 per pound active ingredient, and often lower as a result of volume discounts and other incentive programs. Since the introduction of RR soybeans, the average price of Roundup has fallen about 44 percent.

Together these soybean price reductions saved farmers an estimated $220 million in 1998, according to the NCFAP study. There was a net $360 million reduction is the cost of herbicides and a $160 million increase in RR soybean technology fees (at about $6.00 per acre), producing the estimated reduction of $220 million (Gianessi and Carpenter, 2000). The cost savings were significant -- close to $8.00 per acre across the approximate 27 million acres planted in 1998 to RR varieties.

Low-Dose Options Proliferate

In the last decade the pesticide industry has developed and marketed dozens of new, low-dose soybean herbicides in the imidazolinone and sulfonylurea classes. These products are applied typically in the range 0.004 pounds to 0.125 pounds of active ingredient per acre (page 44, Gianessi and Carpenter, 2000), between six and 187 times lower than the common rate of glyphosate application (0.75 pound per application).

Each year the U.S. Department of Agriculture carries out a field crop pesticide use survey. Soybean herbicide use data are collected and reported by state as part of the survey and summarized nationally (percent acres treated, average one-time rate of application, rate per crop year [the average number of applications times the average rate per application], and pounds applied). All herbicides applied to 1 percent of more of the soybean acres in a state are included in the annual reports, all of which are accessible on the USDA website (see references for urls).

Of the 34-herbicide active ingredients applied to 1 percent of more of national soybean acres in 1999, there were 13 applied at an average rate less than 0.1 pounds of active ingredient per acre. Just five were applied at one pound or more per acre.

USDA's pesticide use data also show that the average rate of glyphosate per crop year was 0.92 pounds of active ingredient. About 30 percent of the acres treated with glyphosate received two Roundup applications.

Soybean Herbicide Use Trends

Prior to the introduction of Roundup Ready soybeans, most farmers applied two to three active ingredients in managing soybean weeds. It usually took about one-half an additional spray, on average, to deal with weeds in no-till systems compared to conventional tillage systems.

Some soybean acres are still treated with the old conventional herbicides applied at rates between 0.8 and 1.5 pounds per acre, again mostly in combinations. Combinations of one or two old herbicides, tank mixed with one or two of the new, low-dose products are increasingly popular. Several new combination herbicide product formulations have been introduced in the last two years in an attempt by manufacturers to make it easier for farmers to purchase and apply two of the company's products, thereby broadening the range of weeds that are adequately controlled – and perhaps competing with or fitting into a RR soybean program.

In studying the impacts of RR soybeans on average herbicide rates, it is important to be careful in assuring that valid comparisons are being made. Throughout this report, remember that –

- Comparisons should not be based on aggregate state or national level data that encompass all sorts of changes in the combinations of soybean herbicides used, individual product rates of application per acre, and the number of times each active ingredient is applied.

- Average total herbicide use in RR planted fields should be compared to average total herbicide use in fields in the same general region planted to conventional varieties in the same year. Comparisons across years can be misleading and are often not valid because of different levels of weed pressure and weather patterns.

- Comparisons should be made within tillage systems; no-till system rates should not be compared to conventional/conservational tillage rates, and vice versa. Resolution is lost when herbicide use data are averaged across all tillage systems.

Table 1.1 reports basic trends in soybean herbicide use per acre across all soybean acres in 1992, 1995, and 1998, as well as use on those acres grown with conventional/ conservation tillage systems and under no-till systems. Throughout this chapter, data on herbicide use in 1995 represents pre-RR soybeans and 1998 data reflects changes after the widespread adoption of RR soybeans, which were planted on about 38 percent of soybean acres that year.

Table 1.1. Trends in U.S. Herbicide Use in Soybean Production Systems

	1992	1995	1998
All Soybeans			
Area Planted (1,000 acres)	52,830	51,840	65,745
Average Number of Herbicides Applied	2.4	2.8	2.2
Total Pounds Active Ingredient Applied	1.16	1.13	1.17
Conventional / Conservation Tillage Systems			
Area Planted (1,000 acres)	45,911	36,879	47,457
Average Number of Herbicides Applied	2.3	2.6	2.1
Total Pounds Active Ingredient Applied	1.13	1.03	1.11
Glyphosate Applied	.56	.56	.92
No-Till Systems			
Area Planted (1,000 acres)	6,919	14,961	18,288
Average Number of Herbicides Applied	2.8	3.3	2.6
Total Pounds Active Ingredient Applied	1.33	1.36	1.32
Glyphosate Applied	.63	.61	.96

Source: USDA Economic Research Service Special Tabulation Number 1, based on soybean field-level sample data collected as part of the "Agricultural Chemicals Usage" survey (National Agricultural Statistics Service, 1999).

Under conventional/conservation tillage, the number of herbicide active ingredients applied rose from 1992 to 1995, but then dropped in 1998 as a result of the emergence of RR soybeans. The trend in total pounds applied fluctuated modestly, dropping about 10 percent from 1992 to 1995 and then increasing in 1998 as RR soybeans gained popularity, and with them higher rate herbicide systems.

In 1998 farmers required on average 3.3 different herbicides in no-till systems to manage weeds (bottom four lines Table 1.1). Again, the introduction of RR soybeans made it possible for farmers to apply markedly fewer herbicides on the average acre. But because moderate-rate glyphosate applications were typically replacing applications of two lower-dose products, there was almost no change in the total pounds applied from 1995 to 1998.

Tables 1.2 and 1.3 show the number of acres, average number of herbicide active ingredients, and differences in herbicide use on fields planted to conventional, non-GMO varieties in contrast to herbicide-tolerant varieties in 1998, the third year of RR soybean variety sales. Not surprisingly, RR soybeans account for the majority of herbicide-tolerant acres treated, about 87 percent.

The first table presents these data on fields managed with conventional/ conservation tillage and the second table covers land planted using the no-tillage system.

Farmers managed weeds on RR soybean fields under conventional/conservation tillage with more than one less herbicide active ingredient; applications of Roundup took the place of applications of two or more other herbicides (Table 1.2).

Table 1.2. Herbicide Use in Fields Planted to Conventional and Herbicide-Tolerant Soybean Varieties in Conventional / Conservation Tillage Production Systems, 1998

	Number Acres Treated (1,000 acres)	Number of Active Ingredients	Pounds Applied Per Acre
Conventional Soybean Varieties	28,340	2.5	1.10
RR Varieties	16,452	1.3	1.14
Other Herbicide-Tolerant Varieties	2,665	2.5	0.97

Source: USDA Economic Research Service Special Tabulation Number 1, based on soybean field-level sample data collected as part of the "Agricultural Chemicals Usage" survey (National Agricultural Statistics Service, 1999).

The tables confirm that no-tillage systems are more herbicide dependent than conventional/conservation tillage systems and that heightened reliance on herbicides is consistent in both fields planted to conventional and herbicide tolerant varieties. No-till systems require about one additional herbicide active ingredient in contrast to conventional/conservation tillage systems and between 10 percent and 20 percent more total herbicide per acre.

The tables also show that at this aggregate level, the average pounds of herbicides applied per acre on RR soybean fields exceed the average pounds applied on conventional varieties by a small margin. But such aggregate data mask more significant differences which will become clear when we turn to assessment of the distribution of herbicide use rates at the field level.

Table 1.3. Herbicide Use in Fields Planted to Conventional and Herbicide-Tolerant Soybean Varieties in No-Till Production Systems, 1998

	Number Acres Treated (1,000 acres)	Number of Active Ingredients	Pounds Applied Per Acre
Conventional Soybean Varieties	8,359	3.6	1.27
RR Varieties	9,042	1.7	1.36
Other Herbicide-Tolerant Varieties	888	3.7	1.42

Source: USDA Economic Research Service Special Tabulation Number 1, based on soybean field-level sample data collected as part of the "Agricultural Chemicals Usage" survey (National Agricultural Statistics Service, 1999).

B. Detailed Examination of Soybean Herbicide Use in 1998

Many people have claimed that Roundup Ready soybeans reduce herbicide use. Such claims can be true in a narrow and selective – and therefore biased -- sense. For example, many RR soybean fields in the first two years of adoption required only a single application of Roundup at a rate of about 0.75 pounds per acre. Many other conventional soybean fields were treated with combinations of moderate to high-dose herbicides at an average combined rate of about 1 pound per acre. In such a comparison, one can conclude accurately that RR soybeans reduced average per acre herbicide use by perhaps 25 percent. But such a selective comparison is no more or less valid than comparing the same RR soybean fields with other fields treated with very-low dose herbicides accounting for a total of just 0.2 pounds of active ingredient – one-fifth the rate on RR soybean acres.

The lack of rigor in analyzing herbicide use rates in RR soybean systems has helped enable the high degree of "spin" that has permeated public discussion of the benefits of RR and other herbicide-tolerant soybean varieties. To develop fair and credible comparisons, we developed a methodology based on actual herbicide use in a specific field, drawing on raw data collected by USDA through its annual pesticide use surveys.

Our estimates count all active ingredients applied on RR soybean acres in contrast to all herbicides applied on fields planted to conventional varieties and other herbicide-tolerant varieties. In two of three special tabulations, we also disaggregated herbicide use data by conventional/ conservation tillage systems in contrast to no-till, to avoid the confusion that arises from mixing tillage systems in a comparison of herbicide use.

To take the analysis one step further, we describe herbicide use along the distribution of soybean fields arrayed by the intensity of herbicide use. This special tabulation allows comparisons of total herbicide use at the low and high ends of this distribution, the first such analysis we know of based on a large sample of actual field-level soybean herbicide use data.

To generate the data in this section comparing field level herbicide use in 1998, we commissioned the USDA's Economic Research Service (ERS) to carry out three special tabulations, since the raw NASS data file needed to carry out such an analysis is not available to the public. The special tabulations were done and paid for by Benbrook Consulting Services under the ERS's "Policy and Procedures on Providing Special Tables or Analyses." Our agreement was dated March 10, 2000 and the data were provided April 11, 2000.

The analysis and results reported here are just a first step in what should be a series of in depth assessments of per acre herbicide use patterns in conventional versus herbicide-tolerant soybean varieties. The same sorts of detailed, field-by-field comparisons are also needed to settle controversy over whether *Bt* corn has reduced insecticide use. Unfortunately, the USDA has not yet carried out such detailed assessments of herbicide use on RR versus conventional fields, despite the intense interest in the results. The special tabulations we commissioned demonstrate how important – and revealing – such in depth analyses will be.

Herbicide Use on Conventional and RR Soybeans

In selected states and nationally, Table 1.4 summarizes total herbicide use measured in total pounds of active ingredient applied per acre in 1998. The tabulation was structured to separate out all survey sample points (fields) planted to a herbicide tolerant variety, in contrast to a conventional variety. Within these two groups of sample points, acres where further divided into those treated with Roundup and those not treated.

Acres Planted Nationally, there was a total of 65.7 million acres of soybeans planted in 1998.

Of these, 36.7 million, or 55.8 percent, were planted to conventional varieties. About 5.2 million were treated with glyphosate applied pre-plant or at-plant as a burndown herbicide. Most of these acres were planted using the no-till system.

RR varieties accounted for 25.4 million acres, or 38.8 percent of total soybean acres planted. There were 3.5 million acres of other herbicide tolerant varieties planted, or about 5.4 percent of total soybean acreage.

Number of Herbicides Applied There were on average 2.2 herbicide active ingredients applied on 65.7 million soybean acres nationwide. On Roundup Ready acres, there were 1.4 products applied, while on other herbicide tolerant varieties, 2.8 products were applied on average.

On conventional varieties on which no glyphosate was applied, 2.7 active ingredients were used, whereas on conventional acres treated with glyphosate, 3.2 herbicides were used on average. Accordingly, the RR system makes it possible for farmers to reduce the average number of herbicides applied by about one-half. Put another way, the ability to apply Roundup post-emergence over soybeans makes it possible for farmers to eliminate applications of about 1.5 other herbicides.

Pounds of Herbicide Applied On the average soybean acre nationwide, farmers applied 1.17 pounds of herbicide active ingredient in 1998. The average glyphosate rate on the 30.7 million soybean acres treated was 0.92 pounds. This rate includes both acres of RR and conventional soybeans.

On Roundup Ready soybeans, the average total amount of herbicides applied was 1.22 pounds per acre and on average, 1.0 pound of glyphosate was applied. On other herbicide tolerant varieties, the average was 1.06 pounds, about 13 percent less.

On acres planted to conventional soybean varieties and not treated with glyphosate, there were an average 1.08 pounds of herbicide applied, 11.4 percent less than on Roundup Ready acres.

Table 1.4. Herbicide Use on Conventional and Herbicide-Tolerant Soybean Varieties in the U.S. and Selected States, 1998

Location	Percent Area Treated	Average Number of Herbicides Applied	All Herbicides Rate Per Acre
National			
Conventional Varieties, no glyphosate applied	47.9%	2.7	1.08
Conventional Varieties, glyphosate applied	8.0%	3.2	1.45
RR Varieties	38.8%	1.4	1.22
Other herbicide-tolerant varieties	5.4%	2.8	1.06
Arkansas			
Conventional Varieties, no glyphosate applied	50.5%	2.5	0.92
RR Varieties	25.5%	1.5	1.50
Iowa			
Conventional Varieties, no glyphosate applied	60.4%	2.4	1.08
RR Varieties	33.8%	1.3	1.40
Illinois			
Conventional Varieties, no glyphosate applied	35.2%	2.8	1.15
RR Varieties	49.9%	1.4	1.09
Minnesota			
Conventional Varieties, no glyphosate applied	71.6%	2.2	0.84
RR Varieties	25.3%	1.2	1.15
Missouri			
Conventional Varieties, no glyphosate applied	57.0%	3.1	1.34
RR Varieties	33.9%	1.4	1.23

Source: USDA Economic Research Service Special Tabulation Number 2, based on soybean field-level sample data collected as part of the "Agricultural Chemicals Usage" survey (National Agricultural Statistics Service, 1999).

National level data masks significant differences across regions. In Arkansas, herbicide use on RR soybeans exceeded conventional soybeans by 63 percent. In Iowa, the margin was 30 percent and in Minnesota, 37 percent. Yet in Missouri and Illinois, herbicide use on conventional soybeans exceeded use on RR varieties by 9 percent and 5.5 percent. Table 1.5 summarizes these differences across all major soybean producing states.

Table 1.5. Differences in Herbicides Applied per Acre Between Roundup Ready and Conventional Soybean Varieties in States Surveyed by USDA, 1998

State	Total Herbicides Per Acre		Ratio RR Soybean Herbicide Rate to Conventional Rate
	RR Soybean	Conventional	
Arkansas	1.50	0.92	1.63
South Dakota	1.42	0.96	1.48
Minnesota	1.15	0.84	1.37
Tenessee	1.78	1.37	1.30
Iowa	1.40	1.08	1.30
Indiana	1.06	0.93	1.14
Ohio	1.17	1.04	1.13
All Surveyed States	1.22	1.08	1.13
Mississippi	1.42	1.38	1.03
Kentucky	1.12	1.09	1.03
Louisiana	1.35	1.34	1.01
Illinois	1.09	1.15	0.95
Kansas	0.85	0.92	0.92
Missouri	1.23	1.34	0.92
North Carolina	1.14	1.30	0.88
Nebraska	1.24	1.45	0.86
Michigan	1.03	1.47	0.70

Source: USDA Economic Research Service Special Tabulation Number 2, based on soybean field-level sample data collected as part of the "Agricultural Chemicals Usage" survey (National Agricultural Statistics Service, 1999).

Distribution of Herbicide Rates

Our third special tabulation of field-level soybean herbicide use data in 1998 focuses on the distribution of herbicide application rates from those farms using the least herbicide to those applying the most. This analysis was run across all soybean acres, as well as all acres broken into conventional/conservation tillage acres versus no-till acres.

Three distributions were developed from field level sample data: one ranked by total pounds of herbicides applied from most pounds to least; a second based on number of herbicide active ingredients applied; and the third, pounds of glyphosate applied from most to least.

Each of the three distributions was divided into 10 deciles representing an equal number of soybean acres. The values at the 90th decile for total pounds of herbicide applied, for example, can be interpreted to mean that 90 percent of soybean acres were treated with herbicides at or below the reported rate; or conversely, that 10 percent of the soybeans were treated at a higher rate than the value reported in the 90th decile.

Table 1.6 shows the distribution of herbicide use rates under conventional/ conservation tillage, representing 47.5 million of the 65.7 million acres of soybeans planted in 1998. At the high end of the distribution, 10 percent of acres were treated with 1.987 or more pounds. At least three herbicides were applied on the 10 percent of the acres treated with the highest number of herbicides. Fields in the top decile were treated with at least 1.13 pounds of Roundup.

At the low-end of the distribution, 10 percent of soybean acres under conventional tillage were treated with 0.058 pounds or less of herbicide, most likely one of the very low dose sulfonylurea or imidazolinone products. These data on total herbicide use make very clear the enormous range in per acre herbicide use -- soybean fields at the top-end of the distribution were treated with at least 34 times more herbicide than fields in the low-end decile.

Table 1.7 presents the same data on no-till acres. There were close to 8 times more total herbicides applied at the top end of the no-till distribution in contrast to the bottom-end. The difference between the top and bottom deciles is less than in the case of conventional/conservation tillage because all no-till acres require a typically intensive pre-plant application of herbicides.

Table 1.6. Distribution of Soybean Herbicide Use Patterns in 1998, Conventional and Conservation Tillage Systems									
Indicator of Use	← Lower Herbicide Use							Higher Herbicide Use →	
	10%	20%	30%	40%	50%	60%	70%	80%	90%
Total Pounds Herbicide Applied Per Acre	0.06	0.47	0.75	0.75	0.95	1.13	1.31	1.57	1.99
Number of Herbicides Applied	1	1	1	1	2	2	2	3	3
Pounds Glyphosate Applied Per Acre	0	0	0	0	0	0	0.75	0.75	1.13

Source: USDA Economic Research Service Special Tabulation Number 3, based on soybean field-level sample data collected as part of the "Agricultural Chemicals Usage" survey (National Agricultural Statistics Service, 1999).

Table 1.7. Distribution of Soybean Herbicide Use Patterns in 1998, No Till Systems									
Indicator of Use	← Lower Herbicide Use							Higher Herbicide Use →	
	10%	20%	30%	40%	50%	60%	70%	80%	90%
Total Pounds Herbicide Applied Per Acre	0.31	0.60	0.75	0.94	1.13	1.34	1.50	1.73	2.34
Number of Herbicides Applied	1	1	1	1	2	3	3	4	5
Pounds Glyphosate Applied Per Acre	0	0	0	0.50	0.75	0.75	0.75	1.13	1.50

Source: USDA Economic Research Service Special Tabulation Number 3, based on soybean field-level sample data collected as part of the "Agricultural Chemicals Usage" survey (National Agricultural Statistics Service, 1999).

In Tables 1.6 and 1.7, fields treated with Roundup, including of course all RR soybean acres, are clustered in the top three (conventional tillage) and top six deciles (no-till systems). In the no-till table, fields under an intensive Roundup program (90th decile) were treated with at least 1.5 pounds of glyphosate, at least three times more than fields in the 40th decile. Roundup use in the 40th decile almost certainly reflects a low-dose of glyphosate added to tank mixes for pre- or at plant applications on fields planted to conventional varieties. (This rate is far below the minimum needed on RR soybean fields, hence the applications must be made pre- or at planting on conventional varieties).

Table 1.8 and 1.9 summarize the differences by tillage system in herbicide use rates along the distribution of all ranked soybean fields. This is done by calculating the ratio of the minimum total pounds of herbicide pounds applied in the top decile compared to the maximum pounds applied in the bottom decile. The next two lines in Tables 1.8 and 1.9 encompass herbicide use in the top two deciles compared to the bottom two, and the bottom two lines cover the top three deciles compared to the bottom three.

For conventional/conservation tillage soybeans, the ratios in Table 1.8 fall from 34 to 3 to 1.7 in comparing the top 10^{th} decile to the bottom 10^{th}, the top 20^{th} to the bottom 20^{th}, and the top 30^{th} to bottom 30^{th}. Since RR soybean acres are concentrated in the top three deciles in both distributions and are largely absent from the bottom three, these comparisons provide a rough approximation of the differences in herbicide use along the distribution of all soybean fields ranked by total pounds of herbicide applied.

The differences in total herbicide use in the top deciles compared to the bottom deciles are less dramatic on fields planted using no-till systems (Table 1.9) compared to conventional/conservation tillage (Table 1.8). This is because all no-till fields have to be treated with a relatively heavy pre- or at plant burndown application, as well as during the growing season. Still, 7.5 times or more herbicide are used in the top decile compared to the bottom and twice or more in the 70^{th} decile compared to the 30^{th}.

Much more accurate and interesting results could be generated by calculating mean herbicide use across all sample points (fields) falling within the deciles and by carrying out the same sort of distributional analyses for soybean fields planted to conventional versus herbicide-tolerant varieties. The cost to commission such more extensive and complicated tabulations was, however, prohibitive.

Table 1.8. The Relative Intensity of Herbicide Use Along the Distribution of All Soybean Fields Surveyed in 1998, Conventional / Conservation Tillage Systems

Decile	Number of Active Ingredients	Total Pounds Applied per Acre	Ratio Top Decile to Bottom Decile Total Pounds Applied Per Acre
Top 10%	3	1.99	34.3
Bottom 10%	1	0.06	
Top 20%	3	1.57	3.3
Bottom 20%	1	0.47	
Top 30%	2	1.31	1.7
Bottom 30%	1	0.75	

Source: USDA Economic Research Service Special Tabulation Number 3, based on soybean field-level sample data collected as part of the "Agricultural Chemicals Usage" survey (National Agricultural Statistics Service, 1999).

Table 1.9. The Relative Intensity of Herbicide Use Along the Distribution of All Soybean Fields Surveyed in 1998, No Till Systems

Decile	Number of Active Ingredients	Total Pounds Applied per Acre	Ratio Top Decile to Bottom Decile Total Pounds Applied Per Acre
Top 10%	5	2.34	7.5
Bottom 10%	1	0.31	
Top 20%	4	1.73	2.9
Bottom 20%	1	0.60	
Top 30%	3	1.50	2.0
Bottom 30%	1	0.75	

Source: USDA Economic Research Service Special Tabulation Number 3, based on soybean field-level sample data collected as part of the "Agricultural Chemicals Usage" survey (National Agricultural Statistics Service, 1999).

C. Representative Major Herbicide Use Programs in 2000 and 2001 on RR Soybeans and Conventional Varieties

Significant shifts have already occurred in herbicide use on fields planted to Roundup Ready soybeans since their commercial introduction in 1996. Several factors have driven the changes, most triggered in one way or another by the remarkable commercial success of this technology.

Rapid increases in the acreage planted to RR soybeans forced other herbicide manufacturers to cut their prices and look for ways to formulate their existing herbicide product lines into combination products that were compatible with RR soybeans and convenient for the farmers planting them. Today, there are more than a dozen new combination products on the market specifically marketed for RR soybean producers.

As noted above, the popularity of RR soybean systems forced other herbicide companies to lower prices, making it possible for farmers to make an additional spray or add in a new active ingredient without increasing per acre herbicide costs. The generally lower prices today have encouraged heavier reliance on herbicides. In the early 1990s in states like Iowa, many farmers were open to sustainable agriculture systems and methods, largely because of potential to lower per acre cash costs. The costs of seed plus herbicides were growing the fastest of any major category of production input (Benbrook, 2000). Up through about 1993 the acreage of row crops planted under ridge till and/or treated with banded (in the row only) applications of herbicides in conjunction with mechanical cultivation had risen steadily.

The introduction of several new soybean herbicides in the mid-1990s, and then RR soybeans in 1996, quickly refocused most farmers on largely herbicide-dependent systems. In the last few years, the percent of soybean acres managed under multitactic weed management systems with lessened reliance on herbicides has shrunk back to a fraction of the level in 1993. The falling cost per acre of herbicide-dependent systems and the simplicity of the RR system have been the major reason why.

Resistance and Weed Shifts

Well before the introduction of RR soybeans, it was known that heavy reliance on any single herbicide, class of herbicides, or weed management tactic in a given field will trigger a shift in the composition of weeds commonly found (Ghersa et al., 1994). Roundup Ready soybean systems are no exception.

Recurrent applications of glyphosate in many corn-soybean production regions in the U.S. have brought about a shift in weed species (Owen, 1999; Hartzler, 1999). Waterhemp, velvetleaf, horseweed, yellow nutsedge and nightshade are more common and difficult to control, especially in RR fields. (Scientists at Iowa State University have done an excellent job tracking and explaining the factors giving rise to weed shifts. These factors include the time period over which weed seeds in the soil are able to germinate and how susceptible a weed is to glyphosate. For more information see http://www.weeds.iastate.edu/).

Some weeds have developed resistance to glyphosate (Horstmeier, April 2001) and others are displaying rising tolerance (Hartzler, 1999). As a result, farmers are compensating by adding additional herbicide active ingredients into their control programs, while others are increasing the rates of Roundup applied in the hope of getting ahead of even tough to control weeds. The dramatic price reductions in recent years have accommodated increased rates without much, if any increase in per acre herbicide expenditures. (For more on resistance to herbicides, see the "International Survey of Herbicide Resistant Weeds" accessible at http://www.weedscience.org/in.asp; or several items on Ag BioTech InfoNet at http://www.biotech-info.net/herbicide-tolerance.html#soy).

As a result of weed shifts and slipping efficacy of Roundup in the control of some weeds, most farmers growing RR soybeans now apply one to three additional active ingredients. An effective pre-plant burndown application is critical in no-till and conservation tillage systems to give RR soybeans a good jump on weeds. Cost-conscious farmers typically include about 0.5 pounds of 2,4-D in a pre-plant or at plant tank mix. The 2,4-D helps manage broadleaf weeds. Another product is typically applied to provide some residual grass control. Popular products include pendimethalin, imazethapry, and treflan. Table 1.10 displays just a few of the popular combinations of products used on conventional and RR soybean varieties. Among post-application programs on conventional soybeans, farmers applying Classic and Assure use only 0.08 pounds of active ingredient at a cost of $24.51 per acre.

Table 1.10 Popular Soybean Herbicide Control Programs Used on Conventional and Roundup Ready Soybean Varieties Under Conventional Tillage, 2000-2001

Type of Program	Herbicides	Pounds applied per Acre	Average Cost ($/lb ai or ae)	Cost per Acre
Conventional Varieties				
PRE	Command (clomazone)	0.65	21.00	13.65
	Choransulam-methyl (FirstRate)	0.04	494.60	19.78
Total program		**0.69**		**$33.43**
POST	Classic (Chlorimuron-ethyl)	0.02	762.30	15.25
	Assure II (quizalofop-ethyl)	0.06	154.40	9.26
Total program		**0.08**		**$24.51**
PPI/POST	Treflan (trifluralin)	0.75	6.90	5.18
	Basagran (bentazon)	0.75	19.30	14.48
Total program		**1.5**		**$19.65**
PPI / POST	Prowl (pendimethalin)	0.85	6.30	5.36
	Pursuit (Imazethapyr)	0.04	248.50	9.94
Total program		**0.89**		**$15.30**
Roundup Ready Varieties				
PRE/POST	2,4-D	0.5	3.00	1.50
	Glyphosate (Roundup Ultra)	0.75	12.80	9.60
	Dual or Lasso (metolachlor or alachlor)	1.6	13.70	21.92
Total program		**2.35**		**$33.02**
PRE/POST	Glyphosate (Roundup Ultra)	0.75	12.80	9.60
	Prowl (pendimethalin)	0.8	6.30	5.04
	Glyphosate (Roundup Ultra)	0.75	12.80	9.60
Total program		**2.30**		**$24.24**
POST	Glyphosate (Roundup Ultra)	0.75	12.80	9.60
	Glyphosate (Roundup Ultra)	0.56	12.80	7.17
Total program		**1.31**		**$16.77**
PRE/POST	2,4-D	0.5	3.00	1.50
	Glyphosate (Roundup Ultra)	0.75	12.80	9.60
Total program		**1.25**		**$11.10**
POST	Glyphosate (Roundup Ultra)	0.75	12.80	9.60
		0.75		**$9.60**

Notes: In "POST" systems, all herbicides are applied at or after planting. All herbicides are applied before planting in "PRE" systems. Herbicides are worked into the soil before planting in a "PPI" (pre-plant incorporated) system.

The cost of this very-low dose program actually compares favorably to a Roundup-based program with RR varieties when the technology fee is counted as a cost of the herbicide program. Under the best of circumstances, farmers in 2001 might get through the season with two applications of Roundup, the second at a reduced rate. This program will cost about $23.00 with the technology fee ($16.77 plus about $6.00 for the technology fee) and results in the application of 1.3 pounds of active ingredient. A typical PRE/POST program in RR soybeans would include two applications of glyphosate and a single application of pendimethalin. This program costs about $30.00 with the technology fee and results in application of about 2.3 pounds of herbicides.

While the "best case scenario" RR system requires less herbicide than the highest-rate conventional systems, it is clear that most RR soybeans will be sprayed with about 0.5 pounds more herbicide than most conventional soybeans in crop season 2001.

There will be exceptions, but the number of conventional, non-GMO acres sprayed with very low rates of herbicides will almost certainly exceed the number of RR soybean acres treated with less than 1.0 pound of herbicides.

D. Roundup Ready Soybean Herbicide Use Reduction Claims by Monsanto and USDA are Deceiving

In the last few years Monsanto, the biotechnology industry, and the U.S. Department of Agriculture have claimed repeatedly that Roundup Ready soybeans reduce herbicide use. As the data cited above shows clearly, this is certainly not the case on the majority of RR soybean acres grown in the United States, nor is it true "on average." Plus, extensive evidence shows that the effectiveness of the Roundup applied in the RR soybean system is slipping. This technology is, to a large extent, a victim of its own success.

In the first few years of commercial RR soybean use, many farmers got through the season with a single application of just one herbicide – Roundup. Between 0.75 and 1.1 pounds of glyphosate active ingredient were applied per acre, clearly not a low rate compared to sulfonylurea or imidazolinone weed management systems requiring between 0.1 and 0.3 pounds of herbicide active ingredient, but about mid-range across all systems. Four years later almost no farmer can get by with just one application of Roundup.

Farmers who applied one application of Roundup on RR beans in 1996 and 1997 are likely to be making two or three in crop year 2001. They will also be applying at least one, and more likely two additional herbicide active ingredients. Some are applying three additional herbicides. Why? Again, the evidence is voluminous, consistent and compellingly clear. Heavy reliance on Roundup in RR soybeans has --

- Triggered significant weed species shifts, favoring those weeds that are not as sensitive to Roundup, as well as those that tend to emerge over extended periods of time, so that some weeds emerge outside the window of time when Roundup applications deliver good control.

- The emergence of resistance in some of the nation's most common, tough to control soybean weeds like waterhemp, coupled with modest to moderate slippage in efficacy in a growing number of other weeds. Slipping efficacy increases the number of escapes and then requires higher application rates to knock back the escaped weeds when a subsequent application is made.

Despite these widely recognized facts, it is still common to encounter claims by Monsanto, the biotechnology industry, the U.S. Department of Agriculture (USDA), and others that RR soybeans reduce herbicide use. How can major companies and a government agency get away with making such claims? It takes a certain amount of care coupled with a little misinformation and a major dose of missing information.

A November 30, 1999 Monsanto document entitled "Chemical Reduction Benefits of Biotechnology Crops" was prepared for the press, political leaders, and PR purposes (Monsanto, 1999). It states that --

> "In a Sparks Commodities, Inc. study conducted in 1996 and 1997, in-season herbicide use in Roundup Ready soybean fields was shown to be less than ***traditional soybean varieties*** by an average of 26 percent and 22 percent respectively, over four regions of the United States." [Emphasis added]

No doubt Sparks Commodities had access to data supporting the above-stated conclusion. Still, this statement falls somewhere between misleading and dishonest. Clearly, the statement leaves much to the imagination. Unless a person knows a lot about contemporary soybean herbicide use patterns, one would conclude from such a statement that RR soybeans make it possible for farmers to reduce per acre herbicide use by about one-quarter on a per acre basis.

But that is not what the statement actually says. Note that the reduced herbicide use claim is based on a comparison to ***"traditional soybean varieties."*** Even this caveat is less than truthful. What Sparks Commodities and Monsanto really mean is that herbicide use in RR soybean fields was 22 to 26 percent less than a selected number of other fields producing conventional soybean varieties.

But not any random set of fields producing conventional soybean varieties, nor even the average field producing conventional varieties; they really mean, in all likelihood, fields planted to conventional varieties on which farmers primarily used conventional, high-dose rate herbicides. Only on such fields would there be a 22 to 25 percent reduction in herbicide use. They surely do not mean the approximate 20 percent (see above data) of fields treated predominantly with combinations of modern, low-dose herbicides applied at a rate of 0.5 pounds or less of herbicide active ingredient per acre (see Table 1.6).

Nor do they mean the approximately 25 percent of RR soybean fields under a Roundup-only program that will, according to Monsanto itself, likely require three applications of Roundup at 32 ounces per acre to achieve satisfactory control (Dunn, 1998). Such a program in 1999 cost about $30.00 per acre for the herbicide and resulted in application of 3.0 pounds of Roundup.

The above data show clearly that much more herbicide is applied to the average RR soybean field compared to the 20 percent of fields reliant largely on low-dose products. Indeed, when compared to soybean weed management systems utilizing the really low-dose herbicides, Roundup Ready fields require more than 10 times the herbicide. But it is inappropriate and misleading to pass off such a selective comparison as representative of the average field, at least in the view of this analyst.

USDA Claims

An April 2000 USDA report, *Genetically Engineered Crops for Pest Management in U.S. Agriculture: Farm-Level Effects* (Fernandez-Cornejo, et al., 2000), makes the following statement in its abstract –

> "...increases in adoption of herbicide-tolerant soybeans led to small but significant increases in yields, no changes in returns, and significant decreases in herbicide use."

It is widely recognized that adopters of RR soybeans are large-scale operators who are aggressive managers. The land they farm is, on average, more productive than land managed by those who are slower to try new technologies. Hence, it is no surprise that on average, RR soybean adopters harvested more bushels per acre than non-adopters. They harvested more bushels before RR varieties hit the market, as well (Economic Research Service, 1999; Miller, 2000; Fernandez-Cornejo et al., 2000; Duffy, 1999). It is unfounded to equate the slightly higher soybean yield on GMO acres as a sign of a "yield advantage," or evidence suggesting the absence of a genetic yield drag.

The slightly higher yields are largely driven by differences in management skills and soil productivity. A third factor is the likely higher degree of herbicide injury on some farms where conventional soybeans are planted and farmers apply modern, low-dose herbicides without adequate care in calibrating equipment to assure that maximum, safe application rates for a given farm's soils are not exceeded.

The claimed "significant decrease in herbicide use" is based on two measures. The first – a decline in herbicide acre-treatments -- has nothing to do with pounds applied. The second measure is the net change in conventional and herbicide-tolerant application rates over time, taking into account the increase in average rates of glyphosate use per acre and the decrease in use of other herbicides. But as explained in more detail below, this comparison encompasses so many changing variables that it is impossible to tell exactly what it means.

The claim founded on reduction in herbicide acre-treatments is fleshed out in a summary article published in Agricultural Outlook, one of USDA's most widely read publications. The August 2000 article states that –

> "In 1998, adopters of herbicide-tolerant soybeans accounted for the largest share of the difference in acre-treatments (54 percent [decrease]), with most of the reduction occurring in the Heartland region." (*Agricultural Outlook*, August 2000, page 13-14).

This decline is the result of one of the major advantages of RR soybeans – the simplicity of the RR system and its reliance on a single herbicide for multiple weed management challenges. But it has little to do with changes in the pounds of herbicides applied per acre, since different soybean herbicides are sprayed at such different rates. In the USDA report, the authors state correctly –

> "...since average application rates vary across pesticide active ingredients, the net effect of substituting one for another may be an increase or decrease in total pounds used." (*Agricultural Outlook*, August 2000, page 15).

On the key question of whether herbicide-tolerant soybeans reduced herbicide use, the August 2000 article states –

> "...as adoption of herbicide-tolerant soybean varieties increased from 7 to 45 percent, the average annual rate of glyphosate application increased from 0.17 pounds per acre in 1996 to 0.43 pounds per acre in 1998, while all other herbicides combined dropped from about 1 pound per acre to 0.57 pounds per acre. That translates into a decline of nearly 10 percent in the overall rate of herbicide use on soybeans during that period." (*Agricultural Outlook*, August 2000, page 14-15).

This statement does ***not*** mean that RR soybeans reduce per acre herbicide use by nearly 10 percent. It refers to aggregate estimates of total herbicide use, not clean comparisons of an acre planted to RR soybeans in contrast to conventional varieties planted on similar soils under the same tillage system. It also does not correct for the timeliness of field operators and the quality of management, nor differences in soil quality.

It also mixes together RR soybeans and two other types of herbicide-tolerant varieties – those engineered to be resistant to the very low-dose sulfonylurea herbicides and those resistant to the low-moderate dose imidazolinone herbicides. While these other herbicide-tolerant varieties account for a relatively small share of total herbicide-tolerant acres, they clearly improve the average performance of all herbicide tolerant varieties in terms of reducing average rates of herbicide use.

Last, the above USDA estimate of a nearly 10 percent decline includes a myriad of changes in herbicide use on the approximate 50 percent of acres not planted to any herbicide tolerant variety.

If reducing the pounds of herbicides applied per acre was among the important goals shaping U.S. soybean weed management systems in the 1990s, the introduction of RR soybean varieties was a major step backwards. It is clear that the average pounds of herbicides applied on soybeans in the U.S. would have dropped by far more than 10 percent from 1995 through 1998 in the absence of RR soybeans. This is because it is likely that the majority of farmers planting RR soybeans – typically top-notch, aggressive managers – would have planted either other varieties tolerant to much lower dose herbicides, or conventional beans in conjunction with mixtures of low- and moderate dose products, or mixtures of low-dose and higher dose “standbys.”

With the wide selection of today’s very competitively priced low-dose soybean herbicides, farmers could easily reduce average application rates to no more than 0.5 pounds per acre, if there were incentives offered to do so. This would cut average soybean herbicide rates about two-thirds from today’s levels and would indeed be a major accomplishment. It also would probably not prove sustainable nor would it prove beneficial because of other agronomic and environmental problems associated with use of many of today’s low-dose herbicides.

II. New Evidence Confirms Roundup Ready Yield Drag

Systematic, independent Roundup Ready yield trials did not get underway on land grant university experiment stations until 1997 (Oplinger et al., 1999). That year relatively few RR soybean trials were conducted and even fewer were designed to provide comparative yield data. Independent U.S. university research on RR soybean field performance really did not get underway in earnest until crop year 1998, the same year over 25 million acres of Roundup Ready soybeans were planted by American farmers.

In 1998 several universities started intensive RR soybean trials to assess herbicide program capability and performance relative to otherwise similar conventional varieties. A team led by University of Wisconsin agronomist Dr. E.S. Oplinger summarized the 1998 trial data across several states in a widely read paper "Performance of Transgenetic Soybeans – Northern US" (Oplinger et al., 1999). Averaged across all varieties tested, the Wisconsin team concluded that RR varieties produced 4 percent fewer bushels. The Oplinger paper raised awareness – and many questions -- in both the farm community and among researchers about the magnitude and causes of the RR soybean yield drag.

Inspired by the Oplinger report and drawing upon it, I analyzed detailed crop year 1998 soybean varietal trials from several land grant universities in major soybean producing states. I extended Oplinger's analysis to include assessment of the performance of the top producing conventional and RR varieties by seed company. The resulting report, "Evidence of the Magnitude and Consequences of the Roundup Ready Soybean Yield Drag from University-Based Varietal Trials in 1998," was released via Ag BioTech InfoNet on July 13, 1999 (Benbrook, 1999; accessible at http://www.biotech-info.net/RR_yield_drag98.pdf).

In the first few weeks after posting the report, over 10,000 copies were downloaded. Almost two years after posting, between 75 and 100 copies of the report are still accessed every week. The current analysis has been shaped by questions raised in response to the 1999 report and many requests for an updated review based on more recent varietal trial and herbicide use data.

A. Crop Year 1999 and 2000 Yield Trials

In crop years 1999 and 2000 over ten thousand comparative RR versus conventional soybean varietal trials were carried out across the country. A comprehensive analysis of all results, like Oplinger's assessment of all trials in the Northern US in 1998, would be a mammoth undertaking. It is also not really necessary since several states have now carried out carefully designed comparative yield trials designed to isolate and quantify the RR yield drag under a defined set of circumstances -- soil type, tillage system, and maturity group.

Taken together the results are reasonably consistent and show that the RR soybean yield drag remains between 5 percent and 10 percent under most circumstances. A cross-section of 1999 and 2000 university trial results are reviewed below.

In quantifying the RR soybean yield drag it is important to not mix apples and oranges and care must be taken to keep confounding variables to a minimum. Ideally, trials should measure RR variety and conventional variety yields within the same maturity group. The plots should be planted in the same location. The same tillage system and planting method should be used. Weed control should be carried out in a way that eliminates weed pressure as a factor depressing yields, and without imposing any injury on the soybean plant.

Ways to access all university soybean trial data from the Internet are presented in the reference section.

Illinois

The University of Illinois carried out soybean trials in 12 locations in 2000. Performance of at least two and sometimes three maturity groups was analyzed at each location. In some locations, there were far more RR varieties tested than conventional varieties within a maturity group, or vice versa, possibly leading to biased comparisons. We discuss results from the nine regions where there was no more than a 10 percent difference in the number of conventional versus RR varieties tested by maturity group. We also excluded data from locations where production or weather related problems clearly skewed the results markedly.

Table 2.1 Yield Drag Between the Top Five Yielding Conventional and Roundup Ready Maturity Group 2 Soybean Varieties Tested in Perry, Illinois Varietal Trials, 2000

Brand	Variety	Average Yield (Bushels/A)	Standard Deviation
Conventional Varieties			
Kruger	K-2711 SCN	57.4	
Golden Harvest	H 2885	56.4	
Kruger	K-2787	56.1	
Kruger	K-2808+	53.9	
Kruger	K-2818+	53.6	
	Average Yield and S.D.	**55.5**	**1.65**
Roundup Ready Varieties			
Brand	**Variety**	**Average Yield (Bushels/A)**	**Standard Deviation**
Stine	EX 2802-4	56.9	
Kruger	K-303+ RR/SCN	53.9	
Kruger	K-303 RR/SCN	53.8	
Horizon	H 299 NRR	52.8	
Garst	D 294 RRN	52.4	
	Average Yield and S.D.	**53.96**	**1.76**
		Difference (bushels/A)	**-1.5**
		Yield Drag: Roundup vs. Conventional	**-2.7%**

Tables 2.1 through 2.9 compare the yields of the top five conventional varieties (ranked by yield per acre) compared to the top five Roundup Ready varieties. Each table reports the average yield in the top five varieties, the difference between the average yield in the top five Roundup Ready varieties compared to the top five conventional varieties, and the RR yield drag.

In a few cases, the average yield of the top five Roundup Ready varieties is greater than the top five conventional varieties. In such cases the yield drag is actually a yield advantage.

Tables comparing the top five conventional and top five RR varieties also report standard deviations in yields, an indicator of how even the yields are among the top varieties. Comparing the standard deviation for the conventional varieties to the RR varieties provides insight into the relative consistency and stability of the genetics behind the top varieties in each group.

Table 2.1 covers trials carried out in Perry Illinois with maturity group 2 soybeans (short-season varieties). The top five conventional varieties averaged 55.5 bushels per acre, while the top five RR varieties reached 53.96 bushels. So in this set of trials, the RR yield drag was 2.7 percent, or about 1.5 bushels per acre.

Table 2.2 Yield Drag Between the Top Five Yielding Conventional and Roundup Ready Maturity Group 3 Soybean Varieties Tested in Dwight, Illinois Varietal Trials, 2000

Brand	Variety	Average Yield (Bushels/A)	Standard Deviation
Conventional Varieties			
Beck's	349	69	
Wilken	3414	68.2	
Garst	D 308	68	
Kruger	K-3555 SCN	68	
Kruger	K-3424+	67.7	
	Average Yield and S.D.	**68.18**	**0.49**
Roundup Ready Varieties			
Brand	**Variety**	**Average Yield (Bushels/A)**	**Standard Deviation**
Kruger	K-349 RR	68.8	
LG	C 9327 RR	67.1	
Asgrow	AG 3201	66.8	
Dekalb	DKB 31-51	66.7	
Kruger	K-323 RR	66.4	
	Average Yield and S.D.	**67.16**	**0.95**
		Difference (bushels/A)	**-1.0**
		Yield Drag: Roundup vs. Conventional	**-1.5%**

The largest RR yield drag observed was 11.1 percent in maturity group 3 varieties tested in Dixon Springs (Table 2.8). In Monmouth maturity group 3 plots, RR varieties displayed a 3.3 percent yield advantage (Table 2.4).

Table 2.10 summarizes our analysis of Illinois trials in 2000. The average yield drag when comparing the top five leading varieties was 2.3 percent, a little larger than the average across all varieties (1.4 percent).

Table 2.3 Yield Drag Between the Top Five Yielding Conventional and Roundup Ready Maturity Group 2 Soybean Varieties Tested in New Berlin, Illinois Varietal Trials, 2000

Brand	Variety	Average Yield (Bushels/A)	Standard Deviation
Conventional Varieties			
Kruger	K-2818+	69.5	
Kruger	K-2808+	69.2	
LG	C 9288	68.9	
Hoblit	HB 291	68.4	
Stine	2990-3	67.5	
	Average Yield and S.D.	**68.7**	**0.78**
Roundup Ready Varieties			
Brand	**Variety**	**Average Yield (Bushels/A)**	**Standard Deviation**
Kruger	K-303 RR/SCN	68.2	
Stine	EX 2802-4	66.9	
Golden Harvest	H 2906 RR	66.3	
Horizon	H 299 NRR	66.3	
Asgrow	AG 2905	65.6	
	Average Yield and S.D.	**66.66**	**0.98**
		Difference (bushels/A)	**-2.0**
		Yield Drag: Roundup vs. Conventional	**-3.0%**

Table 2.4 Yield Drag Between the Top Five Yielding Conventional and Roundup Ready Maturity Group 3 Soybean Varieties Tested in Monmouth, Illinois Varietal Trials, 2000

Brand	Variety	Average Yield (Bushels/A)	Standard Deviation
Conventional Varieties			
United Suppliers/US Se	US S299	61.00	
Merschman	MADISON III	59.70	
Agripro	AP 3009	58.80	
Dairyland	DSR-325	58.40	
Wilken	3431 CN	58.10	
	Average Yield and S.D.	**59.2**	**1.17**
Roundup Ready Varieties			
Brand	**Variety**	**Average Yield (Bushels/A)**	**Standard Deviation**
Merschman	MONROE IIIRR	62.30	
UAP	DG 3399 RR	62.20	
Kruger	K-349 ARR	60.80	
Kruger	K-323 RR	60.30	
Merschman	JEFFERSON IIIRR	60.20	
	Average Yield and S.D.	**61.16**	**1.02**
		Difference (bushels/A)	**2.0**
		Yield Drag: Roundup vs. Conventional	**3.3%**

Table 2.5 Yield Drag Between the Top Five Yielding Conventional and Roundup Ready Maturity Group 2 Soybean Varieties Tested in Erie, Illinois Varietal Trials, 2000

Brand	Variety	Average Yield (Bushels/A)	Standard Deviation
Conventional Varieties			
UAP	DG 3229	71.1	
Deraedt	2311	69.2	
Prairie Brand	PB-230	68.2	
Kaltenberg	KB 270	69.0	
Kaltenberg	KB 248	67.5	
	Average Yield and S.D.	**69.0**	**1.35**
Roundup Ready Varieties			
Brand	**Variety**	**Average Yield (Bushels/A)**	**Standard Deviation**
Dairyland	DSR-228 RR	70.0	
Kruger	K-271 RR	68.5	
Kruger	K-277 RR	68.4	
Kruger	K-222 RR	68.2	
Dekalb	DKB 23-51	68.1	
	Average Yield and S.D.	**68.64**	**0.78**
		Difference (bushels/A)	**-0.4**
		Yield Drag: Roundup vs. Conventional	**-0.5%**

Table 2.6 Yield Drag Between the Top Five Yielding Conventional and Roundup Ready Maturity Group 3 Soybean Varieties Tested in Goodfield, Illinois Varietal Trials, 2000

Conventional Varieties			
Brand	**Variety**	**Average Yield (Bushels/A)**	**Standard Deviation**
Dairyland	DSR-309 STS	64.8	
Kruger	K-3303	64.4	
Growmark	HS 3391	63.8	
Agripro	AP 3009	63.7	
Wilken	3414	63.6	
	Average Yield and S.D.	**64.06**	**0.52**
Roundup Ready Varieites			
Brand	**Variety**	**Average Yield (Bushels/A)**	**Standard Deviation**
Kruger	K-349 RR	64.0	
Kruger	K-323+ RR	60.0	
UAP	DG 3399 RR	59.9	
Dairyland	DSR-357 RR	59.8	
Excel	8298 RR	59.4	
	Average Yield and S.D.	**60.62**	**1.90**
		Difference (bushels/A)	**-3.4**
		Yield Drag: Roundup vs. Conventional	**-5.4%**

Table 2.7 Yield Drag Between the Top Five Yielding Conventional and Roundup Ready Maturity Group 2 Soybean Varieties Tested in DeKalb, Illinois Varietal Trials, 2000

Brand	Variety	Average Yield (Bushels/A)	Standard Deviation
Conventional Varieties			
Prairie Brand	PB-259	74.4	
Golden Harvest	H 2494	72.7	
Golden Harvest	X 92885	72.1	
Kruger	K-2525 A	71.7	
Kaltenberg	X 262	71.7	
Average Yield and S.D.		**72.52**	**1.13**
Roundup Ready Varieties			
Brand	**Variety**	**Average Yield (Bushels/A)**	**Standard Deviation**
Dairyland	DSR-228 RR	72.20	
Wilken	2318 RR	71.20	
Kruger	K-277 RR	70.90	
Kruger	K-267 RR	70.50	
Prairie Brand	PB-2117 RR	70.30	
Average Yield and S.D.		**71.02**	**0.75**
		Difference (bushels/A)	**-1.5**
		Yield Drag: Roundup vs. Conventional	**-2.1%**

Table 2.8 Yield Drag Between the Top Five Yielding Conventional and Roundup Ready Maturity Group 3 Soybean Varieties Tested in Dixon Springs, Illinois Varietal Trials, 2000

Brand	Variety	Average Yield (Bushels/A)	Standard Deviation
Conventional Varieties			
Kruger	K-3777 SCN	69.90	
Kruger	K-3717+	66.80	
Kruger	K-3636 SCN	63.70	
Public Variety	IA 3005	63.40	
Kruger	K-3888 SCN/STS	63.00	
Average Yield and S.D.		**65.4**	**2.95**
Roundup Ready Varieties			
Brand	**Variety**	**Average Yield (Bushels/A)**	**Standard Deviation**
Kruger	K-359 RR/SCN	62.80	
Kruger	K-377+ RR	58.20	
Kruger	K-389 RR/SCN	57.30	
Kruger	K-369 RR/SCN	56.60	
Kruger	K-399 RR	55.50	
Average Yield and S.D.		**58.08**	**2.82**
		Difference (bushels/A)	**-7.3**
		Yield Drag: Roundup vs. Conventional	**-11.1%**

Table 2.9 Yield Drag Between the Top Five Yielding Conventional and Roundup Ready Maturity Group 2 Soybean Varieties Tested in Urbana, Illinois Varietal Trials, 2000

Conventional Varieties			
Brand	**Variety**	**Average Yield (Bushels/A)**	**Standard Deviation**
Hoblit	HB 291	64.40	
Kruger	K-2711 SCN	63.20	
Kruger	K-2770	63.20	
Kruger	K-2787	62.10	
Kruger	K-2818+	61.00	
	Average Yield and S.D.	**62.8**	**1.29**
Roundup Ready Varieites			
Brand	**Variety**	**Average Yield (Bushels/A)**	**Standard Deviation**
Stine	EX 2802-4	67.10	
Asgrow	AG 2703	66.10	
Kruger	K-303 RR/SCN	64.00	
Horizon	H 299 NRR	63.00	
Diener	DB 2977 RR	61.90	
	Average Yield and S.D.	**64.42**	**2.15**
		Difference (bushels/A)	**1.6**
		Yield Drag: Roundup vs. Conventional	**2.6%**

Table 2.10 Illinois Soybean Varietal Trials: Average Yield by Region and Maturity Group for Conventional versus Roundup Ready Varieties, 2000

Region	N=	Maturity Group and Type	All Varieties Tested			Top 5 Yielding Varieties		
			Average Yield (bu/A)	Difference in Yield	RR Yield Drag	Average Yield (bu/A)	Difference in Yield	RR Yield Drag
DeKalb	113	2 (C)	65.9	0.02	0.03%	72.5	-1.50	-2.1%
DeKalb	115	2 (RR)	65.9			71.0		
Dixon Springs	28	3 (C)	56.4	-6.80	-12.1%	65.4	-7.28	-11.1%
Dixon Springs	25	3 (RR)	49.6			58.1		
Dwight	70	3 (C)	63.1	-1.26	-2.0%	68.2	-1.02	-1.5%
Dwight	81	3 (RR)	61.9			67.2		
Erie	113	2 (C)	62.3	-0.10	-0.2%	69.0	-0.36	-0.5%
Erie	115	2 (RR)	62.2			68.6		
Goodfield	70	3 (C)	57.5	-2.87	-5.0%	64.1	-3.44	-5.4%
Goodfield	81	3 (RR)	54.7			60.6		
Monmouth	70	3 (C)	53.7	1.85	3.3%	59.2	1.96	3.2%
Monmouth	81	3 (RR)	55.6			61.2		
New Berlin	30	2 (C)	62.0	0.67	1.1%	68.7	-2.04	-3.0%
New Berlin	28	2 (RR)	62.7			66.7		
Perry	30	2 (C)	49.7	-1.61	-3.2%	55.5	-1.52	-2.7%
Perry	28	2 (RR)	48.1			54.0		
Urbana	30	2 (C)	56.6	3.27	5.5%	62.8	1.64	2.5%
Urbana	28	2 (RR)	59.9			64.4		
			Average RR Yield Drag	**-0.8**	**-1.4%**	**Average RR Yield Drag**	**-1.5**	**-2.3%**

Minnesota

Extensive soybean yield trials were carried out in three locations in Minnesota in 1999. Tables 2.11 through 2.15 compare the results for the top five yielding conventional and Roundup Ready varieties by maturity group, again focusing on those location-maturity group combinations with the largest number, and a roughly equal number of varieties tested. Table 2.16 presents a summary of these Minnesota results.

The RR soybean yield drag is clearly greater on average in Minnesota than Illinois. It averaged about 3.5 bushels in the comparisons of the top five producing varieties, or 6.1 percent (Table 2.16). The RR yield drag 2.4 percent across all varieties tested at the three Minnesota locations.

Table 2.11 Yield Drag Between the Top Five Yielding Conventional and Roundup Ready Maturity Group 4 Soybean Varieties Tested in the Southern Region, Minnesota Varietal Trials, 1999

Brand	Variety	Average Yield (Bushels/A)	Standard Deviation
Conventional Varieties			
US Seeds	USS159	56	
Mycogen	5191	56	
Dahlco	9193	55	
Midwest Seed	G1885	54	
Latham	392Brand	54	
Average Yield and S.D.		**55**	**1.00**
Roundup Ready Varieties			
Wensman	W2198RR	58	
Jung	8192RR	55	
AgriPro	AP1702	54	
Dekalb	CX198RR	53	
Mustang	M-199RR	53	
Average Yield and S.D.		**54.6**	**2.07**
Difference (bushels/A)			**-0.4**
Yield Drag: Roundup vs. Conventional			**-0.7%**

Table 2.12 Yield Drag Between the Top Five Yielding Conventional and Roundup Ready Maturity Group 5 Soybean Varieties Tested in the Southern Region, Minnesota Varietal Trials, 1999

Brand	Variety	Average Yield (Bushels/A)	Standard Deviation
Conventional Varieties			
Latham	Ex-570	56	
Kaltenberg	KB240	56	
Iowa AES	IA2050	55	
Northstar	2002	55	
Gold Country	Clements	55	
	Average Yield and S.D.	**55.4**	**0.55**
Roundup Ready Varieties			
Brand	**Variety**	**Average Yield (Bushels/A)**	**Standard Deviation**
Viking	2000RR	55	
Northstar	2004RR	54	
Dairyland	DSR-241/RR	53	
Stine	1991-4	53	
UPA Midwest	3238RR	52.0	
	Average Yield and S.D.	**53.4**	**1.14**
		Difference (bushels/A)	**-2.0**
		Yield Drag: Roundup vs. Conventional	**-3.6%**

Table 2.13 Yield Drag Between the Top Five Yielding Conventional and Roundup Ready Maturity Group 3 Soybean Varieties Tested in the Central Region, Minnesota Varietal Trials, 1999

Brand	Variety	Average Yield (Bushels/A)	Standard Deviation
Conventional Varieties			
Kaltenberg	KB090	62	
Northstar	933	61	
CroPlan	L0983	60	
Yield King	K-0999A	59	
Topfarm	6077	59	
	Average Yield and S.D.	**60.2**	**1.30**
Roundup Ready Varietites			
Brand	**Variety**	**Average Yield (Bushels/A)**	**Standard Deviation**
KSC/Challenger	K-099A	56	
Mustang	M-091RR	56	
PBR	PBR-0920RR	55	
Kruger	K-099+RR	53	
Renk	RS099RR	52	
	Average Yield and S.D.	**54.4**	**1.82**
		Difference (bushels/A)	**-5.8**
		Yield Drag: Roundup vs. Conventional	**-9.6%**

Table 2.14 Yield Drag Between the Top Five Yielding Conventional and Roundup Ready Maturity Group 4 Soybean Varieties Tested in the Central Region, Minnesota Varietal Trials, 1999

Brand	Variety	Average Yield (Bushels/A)	Standard Deviation
Conventional Varieties			
Stine	1700-6	69	
Kruger	K-1707	69	
Yield King	K-1943+	68	
Kruger	K-1919	66	
KSC/Challenger	K-1991	66	
	Average Yield and S.D.	**67.6**	**1.52**
Roundup Ready Varieties			
Brand	**Variety**	**Average Yield (Bushels/A)**	**Standard Deviation**
Ziller	BT7150R	66	
Renk	RS159RR	64	
Mustang	M-151RR	62	
Kaltenberg	KB161RR	60	
KSC/Challenger	K-141	60	
	Average Yield and S.D.	**62.4**	**2.61**
		Difference (bushels/A)	**-5.2**
		Yield Drag: Roundup vs. Conventional	**-7.7%**

Table 2.15 Yield Drag Between the Top Five Yielding Conventional and Roundup Ready Maturity Group 3 Soybean Varieties Tested in the Northern Region, Minnesota Varietal Trials, 1999

Brand	Variety	Average Yield (Bushels/A)	Standard Deviation
Conventional Varieties			
CroPlan	L0292	49	
Prairie Brand	PB-087	48	
Stine	Ex0300-3	47	
Stine	0280	47	
Mycogen	040	47	
Average Yield and S.D.		**47.6**	**0.89**
Roundup Ready Varieties			
Brand	**Variety**	**Average Yield (Bushels/A)**	**Standard Deviation**
Wensman	W2039RR	44	
Top Farm	6059RR	44	
Hyland	RR Rugged	44	
PBR	PBR-0303RR	43	
Dahlman	903RR	42	
Average Yield and S.D.		**43.4**	**0.89**
Difference (bushels/A)			**-4.2**
Yield Drag: Roundup vs. Conventional			**-8.8%**

Table 2.16 Minnesota Soybean Varietal Trials: Average Yield by Region and Maturity Group for Conventional versus Roundup Ready Varieties, 1999

Region	N=	Maturity Group and Type	All Varieties Tested: Average Yield (bu/A)	All Varieties Tested: Difference in Yield	All Varieties Tested: RR Yield Drag	Top 5 Yielding Varieties: Average Yield (bu/A)	Top 5 Yielding Varieties: Average Yield (bu/A)	Top 5 Yielding Varieties: RR Yield Drag
Central	17	3 (C)	55.5	(3.37)	-6.1%	60.2	-5.80	-9.6%
	10	3 (RR)	52.1			54.4		
	67	4 (C)	60.9	(3.67)	-6.0%	67.6	-5.20	-7.7%
	14	4 (RR)	57.2			62.4		
North	25	3 (C)	42.7	(1.61)	-3.8%	47.6	-4.20	-8.8%
	14	3 (RR)	41.1			43.4		
South	55	4 (C)	50.3	2.07	4.0%	55.0	-0.40	-0.7%
	15	4 (RR)	52.4			54.6		
	71	5 (C)	51.1	0.02	0.0%	55.4	-2.00	-3.6%
	17	5 (RR)	51.1			53.4		
			Average RR Yield Drag	**-1.31**	**-2.4%**	**Average RR Yield Drag**	-3.52	-6.1%

Nebraska

Soybean yield trials were carried out in East Central, South East, and North East regions of Nebraska. Tables 2.17 through 2.20 report the results by maturity group. The average RR yield drag in comparisons of the top five varieties tested was 2.9 percent, and 1.6 percent across all varieties tested.

To limit the impact of sometimes-significant year-to-year fluctuations in yields caused, for example, by adverse weather conditions, Nebraska researchers also summarize their soybean trial results using two-year and three-year averages for a given variety at a given location. Table 2.22 presents an overview of their findings for 1998-2000 testing. It will be important to track changes over the next few years in such averages. If further breeding narrows the RR yield drag, assessment of moving average yields over time across a large number of trials is a good way to capture the degree of progress made.

In addition to the routine soybean varietal trial results covered in Tables 2.17-2.21, a team of researchers at the University of Nebraska carried out a special study designed to focus more sharply on both the magnitude of the RR yield drag and its likely source. The design and results of that important study are the focus of the next section.

Table 2.17 Yield Drag Between the Top Five Yielding Conventional and Roundup Ready 'Early Maturing' Soybean Varieties Tested in the East Central Region, Nebraska Varietal Trials, 2000

Conventional Varieties			
Brand	**Variety**	**Average Yield (Bushels/A)**	**Standard Deviation**
ASGROW	A2553	54.6	
DE SOY	D-2818	51.4	
PUBLIC	NE 3001	51	
KRUGER	K-2818	50.6	
PUBLIC	NE 3399	50	
	Average Yield and S.D.	**51.5**	**1.80**
Roundup Ready Varietites			
Brand	**Variety**	**Average Yield (Bushels/A)**	**Standard Deviation**
STINE	2703-4	48.2	
STINE	2500-4	48.1	
CROPLAN	RT2454	47.9	
KAUP SEED	KS 254R	47	
SANDS	EXP2959RR	46.2	
	Average Yield and S.D.	**47.5**	**0.86**
		Difference (bushels/A)	**-4.0**
		Yield Drag: Roundup vs. Conventional	**-7.8%**

Table 2.18 Yield Drag Between the Top Five Yielding Conventional and Roundup Ready 'Late Maturing' Soybean Varieties Tested in the East Central Region, Nebraska Varietal Trials, 2000

Brand	Variety	Average Yield (Bushels/A)	Standard Deviation
Conventional Varieties			
STINE	3400-0	52.5	
KRUGER	K-3555	51.1	
PUBLIC	NE 3001	50.6	
NUPRIDE	NEMAHA	50.2	
KRUGER	K-3231	50.1	
	Average Yield and S.D.	**50.9**	**0.98**
Roundup Ready Varieties			
Brand	**Variety**	**Average Yield (Bushels/A)**	**Standard Deviation**
LATHAM	EX-1097RR	53	
SANDS	EXP3100RR	51.6	
LATHAM	EX-807RR	50.2	
DYNA-GRO	3286RR	50.1	
EXCEL BRAND	8270RR	48.9	
	Average Yield and S.D.	**50.8**	**1.58**
		Difference (bushels/A)	**-0.1**
		Yield Drag: Roundup vs. Conventional	**-0.3%**

Table 2.19 Yield Drag Between the Top Five Yielding Conventional and Roundup Ready 'Late Maturing' Soybean Varieties Tested in the South East Region, Nebraska Varietal Trials, 2000

Brand	Variety	Average Yield (Bushels/A)	Standard Deviation
Conventional Varieties			
PUBLIC	NE 3399	58.2	
U.S. SEEDS	US S350	57.1	
KRUGER	K-3939+	54.9	
NUPRIDE	NEMAHA	53.5	
SANDS	EXP3599	52.7	
	Average Yield and S.D.	**55.3**	**2.33**
Roundup Ready Varieties			
Brand	**Variety**	**Average Yield (Bushels/A)**	**Standard Deviation**
HOEGEMEYER	305RR	58.4	
MIDLAND	9B340RR	57.3	
SANDS	EXP3100RR	57.2	
KAUP SEED	KS 327R	57.1	
STINE	3503-4	55.6	
	Average Yield and S.D.	**57.1**	**1.00**
		Difference (bushels/A)	**1.8**
		Yield Drag: Roundup vs. Conventional	**3.3%**

Table 2.20 Yield Drag Between the Top Five Yielding Conventional and Roundup Ready Maturity Group 2 Soybean Varieties Tested in the North East Region, Nebraska Varietal Trials, 2000

Brand	Variety	Average Yield (Bushels/A)	Standard Deviation
Conventional Varieties			
STINE	2180	56.8	
SANDS	EXP2599	56.7	
LATHAM	EX-630	56.0	
HOEGEMEYER	232	55.7	
PRAIRIE BRAND	PB-218	55.3	
	Average Yield and S.D.	**56.1**	**0.64**
Roundup Ready Varieties			
Brand	**Variety**	**Average Yield (Bushels/A)**	**Standard Deviation**
PRAIRIE BRAND	PB-2101RR	54.2	
LATHAM	457RR	53.3	
DYNA-GRO	3232RR	51.7	
STINE	2300-4	51.3	
PRAIRIE BRAND	PB-2730RR	51.0	
	Average Yield and S.D.	**52.3**	**1.38**
		Difference (bushels/A)	**-3.8**
		Yield Drag: Roundup vs. Conventional	**-6.8%**

Table 2.21 Nebraska Soybean Varietal Trials: Average Yield by Region and Maturity Group for Conventional versus RoundUp Ready Varieties, 2000

Region	N=	Maturity Group and Type	All Varieties Tested			Top 5 Yielding Varieties		
			Average Yield (bu/A)	Difference in Yield	RR Yield Drag	Average Yield (bu/A)	Difference in Yield	RR Yield Drag
East Central	**46**	Early Maturing Conventional	47.2	-0.22	-0.5%	51.5	-4.04	-7.8%
	7	Early Maturing RR (MG=1-2.5)	46.4			47.5		
	32	Late Maturing Conventional	48.5	-1.54	-3.2%	50.9	-0.14	-0.3%
	38	Late Maturing RR (MG=2.6-5)	47.0			50.8		
South East	**18**	Late Maturing Conventional	51.2	0.72	1.4%	55.3	1.84	3.2%
	37	Late Maturing RR (MG=2.6-5)	51.9			57.1		
North East	**39**	Conventional (MG=2)	50.6	-2.01	-4.0%	56.1	-3.80	-6.8%
	32	Roundup Ready (MG=2)	48.6			52.3		
			Average RR Yield Drag	**-0.76**	**-1.6%**	**Average RR Yield Drag**	**-1.54**	**-2.9%**

Table 2.22 Nebraska Soybean Varietal Trials: Two and Three Year Average Yields by Region, Maturity Group and Type, 1998-2000

		Two Year Average				Three-year Average			
Region	Maturity Type	N	Average Yield (bu/A)	Difference in Yield	Yield Drag RR	N	Average Yield (bu/A)	Difference in Yield	Yield Drag RR
East Central	Early Maturing Conventional	15	55.5	-1.2	-2.2%	7	59.1	-0.7	-1.2%
	Late Maturing Conventional	10	55.2	-0.9	-1.6%	3	56.8	1.6	2.8%
	Roundup Ready	10	54.3	-	-	4	58.4	-	-
South East	Early Maturing Conventional	9	57.5	-0.6	-1.0%	5	56.2	-2.0	-3.6%
	Late Maturing Conventional	6	58.8	-1.9	-3.2%	NA	NA	-	-
	Roundup Ready	11	56.9	-	-	1	54.2	-	-
North East	Conventional	17	46.2	-4.1	-8.9%	10	48.6		
	Roundup Ready	8	42.1			NA	NA		
			Average RR Yield Drag	**-1.2**	**-2.4%**		**Average RR Yield Drag**	**-0.2**	**-0.3%**

B. Unique Nebraska Study Identifies the RR Gene Insertion Process As the Likely Cause of RR Soybean Yield Drag

In a one of a kind study, University of Nebraska scientists carried out a sophisticated experiment in 1998 and 1999 comparing the yield of Roundup Ready soybean varieties to otherwise identical non-GMO varieties. The research was initiated because of questions raised by farmers in the state about the magnitude of the RR soybean yield drag (IANR, 2000).

A variety of experiments were conducted to isolate whether the RR soybean yield drag was related to the impacts of Roundup on the soybeans or some other factor. The scientists compared the yields of 13 RR soybean varieties in fields treated with Roundup at the recommended rates in contrast to other fields planted to the same RR varieties but treated with other weed management systems. In all cases the yields were consistently 55 bushels per acre, eliminating Roundup soybean injury as a possible explanation (IANR, 2000).

The study team, led by Dr. Roger Elmore, then turned their attention to the genetic transformation that renders RR soybeans not susceptible to glyphosate applications. They compared five Roundup Ready varieties to their closest conventional cousins, called isolines, as well as a set of known, high-yielding conventional varieties. In all test plots, weeds were controlled with the same conventional herbicides and by hand, eliminated variable levels of weed management or herbicide injury as complicating variables.

The high-yielding conventional varieties yielded on average 57.7 bushels per acre. Roundup Ready soybeans yielded 52 bushels per acre, placing the magnitude of the RR yield drag relative to the best conventional varieties at 5.7 bushels per acre, or about 11 percent. The most rigorous test to date of the actual RR yield drag came from the comparison of the RR varieties to their isolines, which yielded on average 55 bushels. The yield drag in this comparison was 3 bushels per acre or about 6 percent. The press release describing the Nebraska results states that –

> "This research showed that Roundup Ready soybeans' lower yields stem from the gene insertion process used to create the glyphosate-resistant seed. This scenario is called yield drag. The types of soybeans into which the gene is inserted account for the rest of the yield penalty. This is called yield lag." (IANR, 2000)

A team of Kansas State University scientists carried out a similar, but less sophisticated study in 1998 to assess the impacts of applications of different herbicides on RR and conventional soybean variety yields and to compare RR and conventional soybean yields (Hofer et al., 1999). Like the Nebraska study, no significant differences were found as a function of herbicide program across the three locations where the trials were carried out. At two of the three locations though, the conventional varieties out yielded the RR varieties by about 10 percent. The yield drag was just over 2 percent at the third location.

C. Independent Trial Results Reported by *Farm Journal*

In its Mid-January 2001 issue, the highly respected *Farm Journal* magazine printed an article entitled "Right Seed for You" (Horstmeier, 2001). It reports the yields of conventional and RR soybean varieties in four sets of independent yield trials carried out by four independent testing firms that have been monitoring corn and soybean varietal performance for many years. The tests were designed and carried out to match as closely as possible actual field conditions. Each testing firm picked the most popular conventional and RR soybean varieties in their regions.

Tables 2.23 through 2.25 summarize the results. In each table, we compare the yield of the top RR variety tested from a given company, in contrast to that companies top conventional variety. In the Danville Illinois trials, the top Roundup Ready variety yielded just 1 percent less than each company's corresponding top conventional variety, averaged across the eight companies (Table 2.23). The top DeKalb RR variety out-yielded DeKalb's top conventional variety by 7.6 percent and Pioneer's top RR variety produced 6.9 percent higher yields. But the top conventional varieties of Asgrow and Stine were comparably superior to their top RR varieties.

Table 2.23 Performance of Roundup Ready (RR) and Conventional Soybean Varieties by Company in Independent Trials Reported by *Farm Journal* - - Danville, Illinois 2000

Company	Performance and Type	Variety	Gross Profit	Yield (bu/ac)	RR Yield Drag	
					Bushels per Acre	Percent Yield Drag
Asgrow	Top RR	3201 RR	$256.96	47.2	-3.3	-6.5%
	Top Conventional	3244	$274.58	50.5		
	Low RR	2905 RR	$242.78	44.6	-3.1	-6.5%
	Low Conventional	3469	$259.60	47.7		
Dairyland	Top RR	327 RR	$295.78	54.3	-0.3	-0.5%
	Top Conventional	371	$296.79	54.6		
	Low RR	381 RR	$252.42	46.4	-0.7	-1.5%
	Low Conventional	338	$256.41	47.1		
DeKalb	Top RR	35-51	$268.07	49.3	3.5	7.6%
	Top Conventional	339	$249.26	45.8		
	Low RR	36-51 RR	$241.35	44.4	-1.2	-2.6%
	Low Conventional	300	$248.24	45.6		
Garst	Top RR	294 RR	$268.00	49.3	-0.1	-0.2%
	Top Conventional	285	$268.47	49.4		
	Low RR	355 RR	$256.55	47.2	1.6	3.5%
	Low Conventional	385	$247.86	45.6		
Mycogen	Top RR	5316 RR	$273.61	50.3	-2.1	-4.0%
	Top Conventional	5281	$284.93	52.4		
	Low RR	5366 RR	$252.83	46.5	-0.2	-0.4%
	Low Conventional	5344	$253.88	46.7		
Pioneer	Top RR	93B01 RR	$293.73	54.0	3.5	6.9%
	Top Conventional	9306	$274.73	50.5		
	Low RR	93B53 RR	$277.72	51.1	1.6	3.2%
	Low Conventional	93B82	$269.18	49.5		
Stine	Top RR	3183-4 RR	$289.48	53.2	-4.5	-7.8%
	Top Conventional	3500-0	$313.91	57.7		
	Low RR	3502-4 RR	$268.70	49.4	2.2	4.7%
	Low Conventional	3400-0	$256.85	47.2		
Trisler	Top RR	3297 RR	$267.65	49.2	1.7	3.6%
	Top Conventional	2770	$258.24	47.5		
	Low RR	3597 RR	$246.15	45.3	-0.3	-0.7%
	Low Conventional	3252	$248.20	45.6		
Eight Companies	Top RR Compared to Top Conventional				2.9	-0.9%
	Low RR Compared to Low Conventional				-0.1	-0.3%

Source: Soybean yield and gross profits from the mid-January 2001 *Farm Journal* (Horstmeier, 2001).

Table 2.24 Performance of Roundup Ready (RR) and Conventional Soybean Varieties by Company in Independent Trials Reported by *Farm Journal* - - Oxford, Indiana, 2000 [Companies with four or more RR varieties in trial]						
Company	**Performance and Type**	**Variety**	**Gross Profit**	**Yield (bu/ac)**	**RR Yield Drag**	
					Bushels per Acre	**Percent Yield Drag**
Asgrow	Top RR	2703 RR	$297.64	55.1	-2.7	-4.7%
	Top Conventional	3244	$312.25	57.8		
	Mean RR			51.3	-5.6	-9.8%
	Mean Conventional			56.9		
Mycogen	Top RR	5316 RR	$292.67	54.2	-4.0	-6.9%
	Top Conventional	5281	$314.06	58.2		
	Mean RR			51.8	-2.4	-4.4%
	Mean Conventional			54.2		
Pioneer	Top RR	93B01 RR	$290.54	53.8	-2.2	-3.9%
	Top Conventional	93B82	$301.67	56.0		
	Mean RR			51.1	-4.7	-8.4%
	Mean Conventional			55.8		
Three Companies	Top RR Compared to Top Conventional				-8.9	-15.5%
	Mean RR Compared to mean Conventional				-12.7	-22.7%
Source: Soybean yield and gross profits from the mid-January 2001 *Farm Journal* (Horstmeier, 2001).						

Significantly more trials were carried out in the Oxford, Indiana trials covered in the *Farm Journal* story. Accordingly, we compare the performance of both the top yielding RR and conventional variety, as well as the means of the RR and conventional varieties from the same company. The average yield drag across the three companies among the top yielding RR variety in contrast to the top yielding conventional variety was 15.5 percent (Table 2.24). The average RR yield drag across the three companies based on mean yields was a surprisingly large 22.7 percent.

In trials carried out in Council Bluffs, Iowa, just one RR and one conventional soybean variety was tested from each company, reflecting the top recommended variety for the area. Hence we do not report top, low or mean yields, and instead just compare the single RR to conventional variety tested across the 17 companies in this set of plots. In this set of plots, the average RR yield drag was a remarkable 20 percent. It is likely that some other factors explain a significant portion of this observed yield drag, like heightened vulnerability of RR soybeans to certain common soybean plant diseases. New science pointing to such an explanation is the focus of the next chapter.

Table 2.25 Performance of Roundup Ready (RR) and Conventional Soybean Varieties by Company in Independent Trials Reported by *Farm Journal* - - Council Bluffs, Iowa 2000 [Only one Conventional and RR variety tested for each company]

Company	Type	Variety	Gross Profit	Yield (bu/ac)	RR Yield Drag	
					Bushels per Acre	Percent Yield Drag
Agriland FS	C	3071	$280.96	52.0	-12.9	-24.8%
	RR	3085 RR	$211.30	39.1		
AgriPro	C	2889	$272.43	50.5	-9.1	-18.0%
	RR	2802 RR	$223.29	41.4		
Asgrow	C	2553	$332.48	61.6	-9.9	-16.1%
	RR	2703 RR	$279.07	51.7		
DeKalb	RR	28-51 RR	$275.24	51.0	-1.5	-2.9%
	C	300	$267.30	49.5		
Fontenelle	C	9623	$275.72	51.1	-10.2	-20.0%
	RR	9941 RR	$220.59	40.9		
Garst	C	308	$332.53	61.6	-21.3	-34.6%
	RR	355 RR	$217.62	40.3		
Golden Harvest	C	1316	$318.06	58.9	-14.7	-25.0%
	RR	X92888 RR	$238.68	44.2		
Hoegemeyer	C	275 STS	$271.73	50.3	-7.3	-14.5%
	RR	305 RR	$232.04	43.0		
Kaup	C	2911	$316.93	58.7	-12.9	-22.0%
	RR	284 RR	$247.32	45.8		
Midwest Seed Genetics	C	3141	$310.34	57.5	-13.4	-23.3%
	RR	3060 RR	$238.30	44.1		
Mycogen	C	5261	$325.46	60.3	-20.2	-33.5%
	RR	5316 RR	$216.32	40.1		
Novartis	C	S32-Z3	$287.28	53.2	-5.6	-10.5%
	RR	S30-P6 RR	$256.82	47.6		
Ottilie	C	8330	$279.18	51.7	-6.8	-13.2%
	RR	8293 RR	$242.51	44.9		
Pioneer	C	93B01	$296.51	54.9	-11.6	-21.1%
	RR	93B53 RR	$233.71	43.3		
Renze	C	3361	$264.87	49.1	-4.5	-9.2%
	RR	3111 RR	$240.79	44.6		
Thompson	C	3244	$298.51	55.3	-10.0	-18.1%
	RR	3270 RR	$244.78	45.3		
Wilson	C	3110	$309.26	57.3	-8.8	-15.4%
	RR	2740 RR	$262.06	48.5		
Seventeen Companies	Average yield drag RR soybeans vs conventional				-10.6	-18.9%

Source: Soybean yield and gross profits from the mid-January 2001 *Farm Journal* (Horstmeier, 2001).

III. Lessened Nitrogen Fixation and Weakened Immune System Response are Likely Explanations of Roundup Ready Yield Drag and Crop Losses

Thousands of university soybean trials and several independent studies have shown that there is a Roundup Ready yield drag on the order of 5 percent to 10 percent when RR varieties are compared to otherwise similar conventional varieties grown under similar and favorable conditions. In some comparative trials and on many farms, RR soybeans still yield more bushels per acre, despite the yield drag, because of improved weed control or lessened soybean plant injury, compared to fields treated with low-dose herbicides.

But on other farms RR soybeans perform poorly and the magnitude of the yield drag is much greater than expected. Much work is underway to determine why. Recent evidence points to two likely explanations that probably are interactive in many fields.

First, glyphosate applications over RR soybeans can depress soybean root nodulation and nitrogen fixation and depress yields as a result, as clearly documented in a just-published article in *Agronomy Journal* (King, et al., 2001). Recent experimental work shows that the impact is much greater under drought stress – key evidence that problems with RR soybeans may be related to the secondary impacts of normal physiological responses to stress.

Second, RR soybean plant immune response and defense mechanisms are likely to be temporarily weakened or impaired following applications of glyphosate, especially under certain combinations of field conditions placing plants under abiotic or pest-induced stress.

Recent research suggests that different RR soybean cultivars respond differently to various stresses and that the adverse impacts on nitrogen fixation and immune response can vary widely across varieties, soil types, tillage conditions, and soil moisture conditions. Still, yield losses in many RR soybean fields are likely to have common roots – the genetic transformation creating RR soybeans. The emergence of unexpected and erratic patterns of gene expression in some RR soybeans could be caused by a variety of processes including gene silencing and positional mutagenesis.

A. Evidence of Heightened Soybean Yield Losses

A team of researchers at the University of Arkansas has published an important, first-of-its-kind paper, "Plant Growth and Nitrogenase Activity of Glyphosate-Tolerant Soybean in Response to Foliar Glyphosate Applications" (King, et al., 2001). The team assessed the impact of glyphosate applications to RR soybeans on the efficiency of the soybean plant nitrogen fixation process, which is, of course, critical in achieving optimal yields in this legume crop.

While RR soybean plants are tolerant to glyphosate, the microorganism that affixes nitrogen in soybean plant roots, *Bradyrhizobium japonicum*, is very sensitive to Roundup herbicide. The authors point out –

> "Despite the recognition of *B. japonicum* sensitivity to glyphosate, there have been no reports of the effects of glyphosate on N_2 fixation in GT (glyphosate-tolerant) soybean." (King et al., 2001).

The lack of any independent research until crop year 2000 on glyphosate impacts on N-fixation in RR soybean fields is remarkable, given that adverse impacts on nodulation and nitrogen fixation would be among the first and most obvious concerns any scientist -- or farmer -- would want to explore before widespread adoption of RR soybean technology. The just-published King study is reminiscent of the Losey study on the impacts of *Bt* corn pollen on Monarch butterflies (Losey, et al., 1999) and may well prove even more influential.

The team sprayed Roundup on RR soybeans just as many farmers do, about a week after the soybeans plants emerged and again at three-weeks after emergence. They report that "Our data indicate that applications of glyphosate to young soybean plants delays N_2 fixation." It also delayed and reduced soybean root growth. Under well-watered conditions and in soils with ample soil nitrogen available, depressed N-fixation appears to have little impact on yields (King et al., 2001). But in less fertile soils and/or under drought stress, the team found that the impacts can be significant, with yield losses up to 25 percent compared to controls. Part of the explanation no doubt lies in their finding in greenhouse experiments that glyphosate applications decrease the RR soybean plant root growth (King et al., 2001). It is also well known that the N_2 fixation process in soybeans is very drought-sensitive.

It is also interesting to note that the team documented major varietal differences in the impacts of glyphosate applications on RR soybeans, suggesting that breeders face additional challenges in producing RR varieties that will perform well under a wide variety of field conditions.

Disease Losses

An article in the April 2001 *Farm Journal* magazine quotes the magazine's field agronomist Ken Ferrie as stating –

> "The slide in soybean yields has farmers in many states concerned – and wondering what they need to do. There are lots of puzzle pieces, but disease is one that's easy to pick out."

In 1999 field work, University of Missouri scientists explored the impact of glyphosate and RR soybeans on Fusarium species, common rhizosphere fungi, as well as soybean cyst nematodes, a common pest in much of the Midwest (Kremer et al., 2000). *Fusarium solani* is a particular concern, since it can trigger what is called soybean

Sudden Death Syndrome, a growing problem in several parts of the Midwest in recent years.

Four RR soybean varieties were tested at eight sites across the state. The frequency of Fusarium on roots was studied under three herbicide programs: Roundup alone, Roundup plus a common mixture of conventional herbicides (pendimethalin and imazaquin), and the conventional herbicides alone.

In the plots treated with Roundup alone or with the conventional herbicides, the frequency of Fusarium colonization on roots increased 50 percent to five-fold at two to four weeks after herbicide application. The scientists concluded an abstract presented at the 2000 Annual Meeting of the American Society of Agronomy with the caution –

> "Increased Fusarium colonization of RR soybean roots with glyphosate application may influence disease level."

They continued working on RR soybean-Fusarium dynamics in 2000 field work and in a December 21, 2000 update, the team leader, Dr. Robert Kremer, explained that –

> "There is a natural ebb and flow [in Fusarium populations in the soil], but with Roundup Ready beans treated with Roundup, there was always a spike in the levels of fungi studied."

Moreover, the Missouri researchers note that their work shows that Fusarium levels tend to build up in fields treated year to year with Roundup, an increasingly common occurrence as both RR soybeans and RR corn gain popularity. This suggests that something related to the root exudates or crop residues in RR fields may be having a sustained effect on soil microbial community dynamics, perhaps through the mix of compounds in leaf and root tissues that remain after the crop is harvested and break down in the soil over many months post-harvest.

B. Unexpected Consequences of the Genetic Transformation of Soybeans Conferring Resistance to Roundup

The first evidence of what may be a pleiotrophic effect in RR soybeans emerged in the Southeastern U.S. (A "pleiotrophic effect" is a change in plant physiological performance because of an alleic substitution in a genetically transformed plant). University of Georgia researcher Bill Vencill examined many RR soybean plants that had cracked stems during a particularly hot summer (Coglan, 1999). Vencill replicated the field conditions in growth chambers, comparing the response of RR soybeans to conventional varieties. When soil temperatures reached 45 degrees centigrade, the stems of "virtually all the Monsanto beans split open as the first leaves began to emerge compared with between 50 and 70 percent of the other test plants."

The Georgia research team suspects that the split stalks in RR soybeans grown under heat stress is the result of heightened production of lignin, the woody form of cellulose that makes stalks sturdy enough to support the weight of leaves and soybean pods. In EPSPS-engineered soybeans (i.e, RR soybeans), lignin production goes "into overdrive," making the stalks more brittle and hence more likely to crack when especially dry (Coghlan, 1999).

Unknown to the Georgia researchers, other scientists have been studying soybean lignin biosynthesis for another reason. A USDA-Agricultural Research Service team in Beltsville Maryland has been exploring ways to increase lignin production in sites where soybean cyst nematodes attack soybean plants, as a way to cordon off the pests and limit feeding damage (Suszkiw, 2001). It turns out that soybean lignin production is another important physiological process controlled by phenylalanine. So, when a RR soybean field is treated with Roundup in very hot conditions, the plant's normal genetic response to heat stress might be silencing expression of the engineered EPSPS gene, or turning back on the normal EPSPS gene, remnants of which may persist in the genome of some RR varieties.

The emergence of brittle RR soybean stalks, under certain conditions, is an example of the complex combinations of circumstances that can, and sometimes do give rise to unintended and detrimental changes in GMO crop physiology and performance. For reasons explained below, excessive heat is almost surely not the only abiotic stress with the capacity to impact RR plants in such unexpected ways. The King study showed clearly that drought can also alter RR soybean performance (King et al., 2001).

The Unique Importance of the RR Soybean Genetic Modification

The herbicidal activity of glyphosate was discovered in 1970 by a team of Monsanto scientists led by Dr. John Franz. According to a March 2001 article in the *Proceedings of the National Academy of Sciences* written by a two Monsanto scientists, the biochemical mode of action of glyphosate is now almost fully understood (Alibhai and Stallings, 2001). By 1972 Monsanto understood that it worked through "inhibition of aromatic amino acid biosynthesis in plants."

In 1980 glyphosate's target enzyme was identified in the shikimate pathway: 5-*enol*pyruvoylshikimate-3-phospahte synthase, or EPSPS for short. The Oxford Dictionary of Biochemistry and Molecular Biology (2000 Edition) describes the shikimate pathway as "a metabolic tree with many branches." It is the metabolic pathway leading to the production of the aromatic amino acids phenylalanine, tyrosine, and tryptophan. The shikimate pathway and these aromatic amino acids play several critical roles in normal cell function, plant growth, and disease and stress responses. The recent *PNAS* article goes on to state that –

> "The importance of the shikimate pathway in plants is further substantiated by the estimation that up to 35% or more of the ultimate plant mass in dry weight is represented by aromatic molecules derived from the shikimate pathway."

Roundup kills plants by binding to EPSPS and thereby inhibiting aromatic amino acid biosynthesis. Plants are made tolerant of Roundup through the insertion of a transgene that is constructed primarily from bacterial genes. The inserted version of the gene coding for EPSPS in RR plants undercuts the ability of EPSPS to absorb glyphosate. Because no glyphosate is absorbed, the shikimate pathway keeps working largely as it normally would and plant growth can proceed unimpaired.

The discovery of two extra bacterial DNA sequences in RR soybeans in 2000 raises new and rekindles old concerns (Palevitz, 2000). The extra DNA inserts cause "no [human] safety concerns" according to Monsanto scientists. But since Monsanto research shows that the inserts came from the EPSPS structural gene, it is conceivable that the extra DNA may, under some circumstances, play a role in abnormal patterns of EPSPS gene expression, in turn impacting production of aromatic amino acids or other secondary compounds including phtyoestrogens and isoflavinoids, which are also sometimes depressed in RR soybeans (Lappe et al., 1999). While Monsanto's Dr. Roy Fuchs claims that "The original source of the [extra] EPSPS sequences...is not known nor is it important," other scientists are not so certain. University of Georgia geneticist Dr. Richard Meagher is among them –

> "I don't worry about it [the extra DNA inserts] expressing anything. I worry more about it disrupting something." (Palevitz, 2000)

Field Evidence Suggests Problems in RR Soybean Shikimate Pathway Responses

Why did the Missouri research team find that Fusarium levels in soil are building over time and that spikes occur following Roundup application on RR soybeans? These are important, practical questions of significance to all farmers planting RR soybeans, since a variety of Fusarium species are "almost always found in soybean fields." Given that Roundup is applied over the top of the growing soybean plants and is not persistent in the ambient environment, relatively little enters the soil and direct contact with Fusarium spread through the rhizosphere would, in most cases, be limited. A more plausible explanation for the higher frequency of colonization in the Missouri RR fields is an incomplete or altered soybean plant defense response, perhaps in combination with unanticipated responses to applications of glyphosate itself.

Since this experiment found elevated Fusarium colonization in RR soybeans treated with Roundup, but not RR soybeans treated with conventional herbicides, the evidence suggests that depression in plant immune response may be linked somehow to the response of RR soybean plants following treatment with Roundup. Apparently, the genetic transformation that makes the plants able to withstand Roundup may also be impacting the plant's immune response. Remember that the RR soybean transformation targets the EPSPS protein, itself critically hard-wired to major plant physiological and immune response processes. In the March 2001 *PNAS* article by two Monsanto scientists, they highlight the significance of EPSPS by saying that –

> "The EPSPS reaction is the penultimate step in the shikimic acid pathway for the biosynthesis of aromatic amino acids (Phe, Tyr, and Trp) and many secondary metabolites, including tetrahydrofolate, ubiquinone, and vitamin K." (Alibhai and Stallings, 2001)

Also recall the earlier quoted passage, which points out that up to 35 percent of soybean plant mass is represented by aromatic molecules derived from the shikimate pathway. It is clear, then, that the genetic transformation which makes RR soybeans able to tolerate glyphosate entails changes in the gene which serves as a sort of master control switch, if not the "nerve center," of perhaps the most important biochemical pathway in all plants.

As a result it is not surprising that such genetic transformation might, under some circumstances, lead to unanticipated and unintended consequences, many linked in one way or another to the plant's ability to fully deploy pest-induced defense mechanisms or respond to other sources of stress. Indeed, there are probably many different combinations of conditions that can induce unusual protein-regulated stress and immune responses that in turn interact with, and perhaps impair, the ability of engineered EPSPS to carry out its many other important regulatory functions (Facchini et al., 2000). Indeed, the complete absence of such unintended effects in RR soybeans is almost unimaginable given the wide range of stress response and DNA repair tools that RR soybean plants invoke in response to abiotic stress, pest feeding, or perceived threats to genomic integrity.

Synthesis of Aromatic Amino Acids is Sometimes Depressed in RR Plants

Some studies carried out by Monsanto contradict the company's assertion that the genetic transformation making plants Roundup Ready has no effect on the biosynthesis of aromatic amino acids (Padgette et al., 1995; Sidhu et al., 2000).

To establish the nutritional equivalence of Roundup Ready soybeans prior to regulatory approval in the United States, Monsanto commissioned a number of composition studies of RR soybeans carried out at multiple sites. One such RR soybean compositional study was carried out in 1992 in Puerto Rico by a team of Monsanto scientists led by Dr. Stephen Padgette. While the results of the Puerto Rico study are often cited as supporting the conclusion that there were no compositional differences between the RR soybean lines tested and a conventional control line, no published reports include the actual data. Recently, the Puerto Rico data surfaced (Padgette et al., 1995). The study encompassed 50 characteristics including aromatic amino acids, fatty acids, isoflavones, trypsin inhibitor, and lectin.

The title of the research paper contains the only direct statement of its findings – "The Composition of Glyphosate-tolerant Soybean Seeds is Equivalent to Conventional Soybeans." While true for about 40 of the 50 characteristics, there was a statistically significant depression in phenylalanine levels in one of the two RR lines tested. The mean phenylalanine level dropped from 2.22 grams per 100 grams dry weight in the control line to 2.14 in the 40-3-2 RR seed line. In addition, lectin levels were also depressed in both RR seed lines, falling from 5.7 HU/mg extracted protein to 4.1 and 3.6 HU/mg extracted protein in the two RR seed lines.

The impact on lectin levels might explain the observed greater vulnerability of RR soybeans to some common soybean insects. Lectins play a variety of roles in plant metabolism, especially in binding various sugars. Some lectins also have insecticidal properties and have, for this reason, been the focus of rDNA transformations to create insect-resistance plants.

Monsanto research carried out on Roundup Ready corn also assessed impacts on EPSPS-controlled aromatic amino acids. The major published paper on Roundup Ready corn composition appeared in the May 31, 2000 *Journal of Agricultural Food Chemistry* (Sidhu et al., 2000). While there were no statistically significant differences observed in phenylalanine levels in RR corn lines compared to non-engineered control lines, there was a statistically significant reduction in tyrosine levels in the 1996 trials, but not those carried out in 1997 trials. Tyrosine is one of the three major aromatic amino acids produced within the shikimate pathway and controlled to a large extent by the engineered EPSPS gene in RR varieties.

The authors dismiss the 1996 tyrosine finding as “unlikely to be of biological significance” because of the lack of a difference in 1997 and the absence of any differences in poultry growth rates in a feeding trail also covered in the May 2000 article.

The lack of response in a poultry feeding trial sheds no light on whether depressed tyrosine levels in 1996 could trigger problems in RR corn plant defense mechanisms or physiological development. Moreover, given that there were only two years of data from a small number of sites under carefully controlled conditions reducing the normal range of corn plant stresses, it remains to be established whether depressed tyrosine levels are the norm or exceptional in RR corn lines, especially in the face of abiotic stress or pest pressure.

Evidence of even minor depression of phenylalanine and trypsin at the end of the crop season in harvested soybeans is significant because it is very likely that the degree of depression in the levels of these aromatic amino acids was much greater in the days, and perhaps weeks after applications of glyphosate. The King team showed that RR soybean plant nitrogen fixation, root mass, and yields can recover by the end of the year when plants are not drought stressed and when there are ample N reserves in the soil. Under similar favorable conditions, it is likely that phenylalanine and tyrosine levels also recover by the time the soybeans are harvested.

But in conditions that impose added stress on RR soybean plants, aromatic amino acid levels are probably depressed more dramatically, at least for a short period, than when plants are growing under ideal conditions (Facchini et al., 2000). It probably also takes longer for plants weakened by abiotic or pest stresses to recover and produce normal levels of these key regulatory proteins. This delay in recovery to normal protein levels opens a window of opportunity for soil-borne pathogens and other pests. In some fields the muted RR soybean immune response allows pathogens to build up to levels where the plant must invest significant resources over an extended period to combat the pest and in some cases, the diverted energy imposes an irreversible yield penalty on the plant, despite its full recovery prior to harvest.

Phenylalanine Plays a Critical Role in Triggering Plant Defenses

Depressed production of phenylalanine in RR soybeans, as noted in the Puerto Rico trials, can have important plant defense consequences. Scientists have now documented, for example, the critical role of phenylalanine in the triggering of Systemic Acquired Resistance (SAR), a plant's generic immune response to a variety of pest attacks (Dempsey et al., 1999). Efforts are underway in many research groups to identify genetic modifications that might serve as a generic on-off switch for SAR and several groups believe they are close to isolating such genes (Verberne et al., 2000; Osusky et al., 2000).

Phenylalanine is the critical precursor chemical for a cascade of reactions leading to the triggering of SAR (Yang et al., 2001). This was among the important findings reported in a January 16, 2001 article in the *Proceedings of the National Academy of Sciences* assessing the biochemistry of a plant's hypersensitive response (HR). HR is a form of programmed cell death that plays a critical role in the cascade of events that follows attack by a herbivore, plant pathogen, or physical injury. Research in tobacco shows that when plants are wounded, protein kinases are produced that trigger the expression of two defense genes, HMGR (3-hydroxy-3-methylglutaryl CoA reductase) and PAL (L-phenylalanine ammonia lyase). The authors point out that these protein kinases "control multiple defense responses against pathogen invasion," most of which are either triggered or controlled by chemicals produced within the shikimate pathway.

Further clear evidence of the role of the shikimate pathway, the ESPSP gene, and phenylalanine in triggering systemic acquired resistance is reported in a 1998 report in *Plant Physiology* (Smith-Becker, et al., 1998). Cucumber leaves were infected with *Pseudomonas syringae* pv. *syringae* by the University of California-Riverside research team. The first key step in the immune response triggered a transient increase in phenylalanine ammonia lyase (PAL). Soon thereafter salicylic acid began to build up in phloem fluids "at about the same time PAL activity began to increase." And then as the phloem moves through the plant, the salicylic acid carried along with it delivers an advance warning of trouble coming, triggering the initiation of a cascade of responses that together account for the phenomenon called systemic acquired resistance (SAR).

The importance of salicylic acid is well known and includes "the induction of local and systemic disease resistance, the potentiation of cell death, and the containment of pathogen spread" (Dempsey et al., 1999). Salicylic acid controls these plant defense mechanisms through the balancing of subtle biochemical processes, each controlled in turn by certain genes and regulatory compounds. Even subtle and short-term changes in aromatic amino acid levels in RR soybeans can, at times of plant stress, mute the full expression of a plant's defense mechanisms. Two plant biologists highlighted the risks of altering major metabolic pathways inn a recent review article –

> "...these efforts to alter plant metabolic pathways...have often produced unpredictable results, primarily die to our limited understanding of the network architecture of metabolic pathways...Most current models of metabolic regulation in plants are still based on individual reactions, and do not consider the integration of several pathways sharing common branch points." (Facchini et al., 2000).

Clearly, RR soybean yields would be much lower and more erratic if aromatic amino acid biosynthesis were routinely and significantly depressed. The fact that problems tend to arise in conditions of abiotic or pest stress suggests that either gene silencing or an insertional effect explain the larger than normal yield losses in some fields.

In some RR varieties growing under stressful conditions, the engineered EPSPS gene that keeps glyphosate from binding to EPSPS in RR soybeans may be partially silenced by other genetic responses of the plant that are part of the plant's attempt to deal with drought, for example. In such fields, the RR soybeans might be producing a mixture of the engineered and conventional EPSPS. As a result, soybean plants would suffer some degree of injury from exposure to glyphosate, impairing all sorts of biochemical and physiological processes, including of course plant defense mechanisms.

Research done at the Plant Biotechnology Institute in Saskatoon, Saskatchewan, Canada focused on the stability of transgene expression in genetically engineered spring wheat cultivars (Demeke et al., 1999). They report that unstable gene expression can arise when multiple copies of a transgene are incorporated in a genome or when the introduced genes share sequence homology (are genetically similar) to endogenous genes. They also point out that transgene expression can be impacted by the DNA immediately surrounding the locus where the transgene is expressed; recall the extra DNA found in RR soybeans by Monsanto scientists was lodged right next to the engineered EPSPS gene. According to the Canadian researchers –

> "Gene silencing is a common phenomenon in transgenic plants. The two kinds of gene silencing include (1) transcriptional gene inactivation, as a result of promoter in-operation, and (2) post-transcriptional gene inactivation that occurs when produced mRNA fails to accumulate or encode a product." (Demeke et al., 1999)

Gene silencing is one of the major reasons why, over time, it becomes more and more likely that the soybean plant's natural DNA repair mechanisms will find a way to recognize, and then partly repair the "damage" done when the modified EPSPS gene was first transferred into the soybean genome. One of the basic DNA repair strategies used by all organisms is to turn off, or subdue the expression of foreign DNA – hence the phrase "gene silencing."

Positional mutagenesis offers a second possible explanation for how and why, in some fields of RR soybeans, key plant defense mechanisms seem to be less effective than normally the case. A number of natural factors can cause mutations and/or trigger movement of genes within a genome or changes in the levels of expression of genes. The consequences in RR soybeans may include a depression in phenylalanine and lectin levels, making plants somewhat more susceptible to common pests than non-engineered varieties.

Years of research will be required to sort out the dizzying array of environmental, plant health, and pest complex factors that can combine to cause changes in the production of aromatic amino acids in RR soybean plants. Data from the U.S. suggests strongly that soybean plants are more vulnerable to disease pathogens when grown in heavy soils and humid areas with ample rainfall. Such regions can support high soybean yields in years when everything goes right, but are also more prone to sometimes-serious disease losses at the expense of both farmers and society.

Appendix 1. Herbicide Common and Chemical Names, Major Manufacturers and Average Contemporary Cost per Pound of Active Ingredient

Common Name	Active Ingredient(s)	Major Manufacturer	Average Cost ($/lb ai or ae)
2,4-D	2,4-D	Various	$3.00
Aim	carfentrazone-ethyl	FMC	$311.90
Assure II	quizalofop-P-ethyl	Dupont	$154.40
Authority	sullfentrazone	FMC	$60.60
Axiom	flufenacet + Metribuzin	Bayer	$27.20
Basagran	bentazon	BASF	$19.30
Blazer	acifluorfen	BASF	$34.40
Boundary	s-metolachlor + metribuzin	Syngenta	
Broadstrike	flumetsulam	Dow Agro	
Broadstrike + Dual	Flumetsulam + metholachlor	Syngenta	$10.93
Canopy	chlorimuron-ethyl & metribuzin	Dupont	$48.17
Classic	chlorimuron	Dupont	$762.30
Cobra	lactofen	Valent	$66.90
Command	clomazone	FMC	$21.00
Conclude	sethoxydim + bentazon + acifluofen	BASF	
Domain	thiophanate-methyl	The Scotts Company	$22.80
Dual II Magnum	metolochlor	Syngenta	$13.80
Extreme	imazethapyr + glyphosate	BASF	$7.60
FirstRate	cloransulam methyl	DowAgro	$494.60
Flexstar	fomesafen	Syngenta	$51.10
Freedom	alachlor + trifluralin	Monsanto	$1.10
Frontier	dimethenamid	BASF	$14.50
Fusilade DX	fluazifop	Syngenta	$64.50
Fusion	fenoxaprop-P-ethyl & fluazifop-P-butyl	Syngenta	$55.10
Galaxy	bentazon + acifluorfen	BASF	$17.70
Gauntlet	sulfentrazone + cloransulam-methyl	FMC	
Glyphomax	glyphosate	Monsanto	
Gramoxone	paraquat	Syngenta	$11.40
Harmony GT	thifensulfuron	Dupont	$246.50
Lasso	alachlor	Monsanto	$5.80
Lorox	linuron	Dupont	$18.53
Manifest	sethoxydim + bentazon + acifluorfen	BASF	$18.20
Outlook	dimethenamid	NA	
Partner	alachlor	Monsanto	$6.10
Pendimax	pendimethalin	BASF	
Pentagon	pendimethalin	BASF	
Pinnacle	thifensulfuron	Dupont	$2,514.50
Poast	sethoxydim	BASF	$46.90
Poast Plus	sethoxydim	BASF	$53.00
Prowl	pendimethalin	BASF	$6.30
Pursuit	imazethapyr	BASF	$248.50
Pursuit Plus	imazethapyr & pendimethalin	BASF	$15.90
Python	flumetsulam	Dow Agro	$184.90
Raptor	imazamox	BASF	$505.50
Reflex	fomesafen	Syngenta	$44.40
Resource	flumiclorac	Valent	$193.80

Appendix 1. Herbicide Common and Chemical Names, Major Manufacturers and Average Contemporary Cost per Pound of Active Ingredient

Common Name	Active Ingredient(s)	Major Manufacturer	Average Cost ($/lb ai or ae)
Rezult B	bentazone	BASF	
Rezult G	sethoxydim	BASF	
Roundup	glyphosate	Monsanto	$10.00
Roundup Ultra	glyphosate	Monsanto	$12.80
Sceptor	imazaquin	BASF	$123.30
Select	clethodim	Tomen Agro	$95.60
Sencor	metribuzin	Bayer	$26.70
Sonalan	ethalfluralin	Dow Agro	$10.60
Squadron	pendimethalin + imazaquin	BASF	$25.64
Steel	imazaquin + imazethapyr + pendimethalin	BASF	
Stellar	flumiclorac + lactofen	Valent	$67.40
Storm	bentazon + acifluorfen	BASF	$19.90
Synchrony STS	chlorimuron + thifensulfuron	Dupont	$352.60
Touchdown	glyphosate-trimesium (sulfosate)	Syngenta	$9.90
Treflan	trifluralin	Dow Agro	$6.90
Weedone	2,4-D	Nufarm	$3.00
Zorial	norflurazon	Syngenta	$16.50

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