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Economic and Environmental Impacts of First Generation Genetically Modified Crops:

Lessons from the United States

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Economic and Environmental Impacts of First Generation Genetically Modified Crops: Lessons from the United States

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TABLE OF CONTENTS

Executive Summary

1. Introduction

This paper brings together a wide reading of the current agricultural research on genetically modified organisms, and data on planting, use rates and yields, focusing specifically on three crops: Roundup Ready (RR) soy, Bt cotton, and Bt corn. With a view to drawing out the implications for crop management strategies in the U.S. and Argentina—the two biggest users of the new technologies—it first looks at rates of adoption, herbicide use rates and yield data.

It then looks at the environmental effects of current practice. Those effects include several pieces of environmental good news, including benefits to soil conservation from new cropping techniques, and the benefits of using glyphosate in combination with RR soy, replacing more toxic and persistent herbicides. But they also include some worrying news. Poor management of the new technologies risks undermining their effectiveness, as selection pressures lead to weed and pest shifts, and to increased resistance. The study predicts that with Argentine levels and patterns of use, these problems should be surfacing soon, if they are not already.

The study also looks at emerging issues that may impact the performance of RR soybean cultivars. New research shows that the process of making soy cultivars Roundup Ready may also impair their physiological performance under certain types of stress and growing conditions. Other research looks at the changes in soil microbial communities that are brought about by high levels of glyphosate use. Particularly worrying are the observed links between glyphosate use and increased levels of Fusarium – a fungus associated with a number of crop and livestock diseases. Also worrying are the observed negative effects of glyphosate on soybean root development and nitrogen fixation.

Based on what we know today, the consequences of these environmental impacts and ecological responses are largely economic, played out in terms of crop yields and costs of crop production. The study makes a number of recommendations aimed at maintaining the benefits of the new technologies, including reducing the ratio of acreage devoted to RR vs. conventional soybean varieties, diversifying weed management systems and technologies, and reducing the over-reliance on any single strategy.

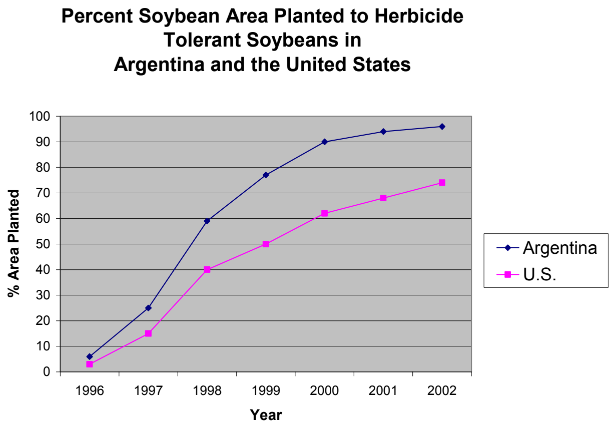
2. Rates of adoption, herbicide use rates and yield data

2.1. Adoption of the technology

Farmers in the U.S. and Argentina first planted RR soybeans in 1996. The rates of adoption in the two countries have followed roughly similar trajectories, as shown in Figure 1.

Growth in percent hectares/acres planted to herbicide-tolerant soybean varieties rose rapidly to about 90 percent in Argentina in 2000 and over 95 percent in 2002, but grew more slowly from 1998 to 2002 in the United States, reaching around 75 percent in 2002. Rates may go marginally higher in the U.S. in the next few years but almost certainly will not reach the extent of adoption in Argentina.

Figure 1: Adoption of the technology: US and Argentina



2.2. Herbicide use rates

Basic data on area planted to RR varieties and glyphosate use rates in Argentina and the United States in 2000 are presented in Table 1. The table reports area planted to soybeans in both countries under conventional/conservation tillage systems, no-till, and all tillage systems. The number of glyphosate applications made and average rates per application and crop year1 are estimated, as well as total use in kilograms and pounds and liters and gallons. Both English and metric units are presented in Table 1 for ease of comparison.2

On average soybean growers in Argentina make 2.3 glyphosate applications per year, compared to an average of 1.3 in the United States. Most of the difference is caused by the greater percent of Argentina soybeans planted using the no-till system. Essentially all no-till cropland is treated with a burndown application of glyphosate herbicide soon before or at planting, as well as one or two applications during the season. In Argentina, about one-half RR soybean hectares need to be treated twice during the season, whereas multiple applications in the U.S. are less common.

The pesticide industry in the U.S. has responded to the emergence of RR soybeans by offering dozens of new specially formulated mixtures of other herbicides designed to augment weed control in fields planted to RR soybeans. New pre-mix products have

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[1] The average rate per crop year is calculated by multiplying the average number of applications by the average rate of application.

[2] Throughout this paper, results from research done in the U.S. are reported using English units, with some key findings also reported in metric units. Appendix tables report the conversion factors used.

Table 1: Extent of Adoption, Rates of Application and Use of Glyphosate (Liters and Pounds of Active Ingredient) in the Production of Roundup Ready Soybeans in the United States and Argentina: Crop Year 2000 Estimates [Bold cells are data values from original sources and may differ modestly from calculated values]

	Soybean Hectares Planted	**Soybean Acres Planted**	**Percent Hectares/ Acres Planted to RR Soybeans**	**Hectares Planted to RR Soybeans**	**Acres Planted to RR Soybeans**	**Glyphosate Active Ingredient**							**Liters Applied Formulated Product**	**Gallons Applied Formulated Product**
						Number of Applications	**Average Rate of Application (Kilograms per Hectare)**	**Average Rate of Application (Pounds per Acre)**	**Rate per Crop Year (Kilograms per Hectare)**	**Rate per Crop Year (Pounds per Acre)**	**Kilograms Applied**	**Pounds Applied**		
Conventional/ Conservation Tillage														
Argentina	3,096,000	7,647,120	75.0%	2,322,000	5,737,662	1.9	1.10	1.0	2.09	1.87	4,852,980	10,708,600	10,108,757	2,677,150
United States	19,732,029	48,721,060	52.0%	10,252,801	25,334,951	1.1	0.67	0.6	0.73986	0.66	7,585,638	16,721,068	15,800,883	4,180,267
No-Till with Roundup Burndown														
Argentina	7,224,000	17,843,280	96.0%	6,935,040	17,129,549	2.5	1.20	1.07	3.0	2.68	20,805,120	45,890,061	43,337,065	11,472,515
United States	9,718,761	23,996,940	64.0%	6,215,246	15,358,042	2	0.78	0.7	1.57	1.4	9,754,207	21,501,258	20,318,013	5,375,315
All Tillage Systems														
Argentina	**10,320,000**	25,490,400	**90.0%**	9,288,000	22,941,360	**2.3**	**1.20**	1.07	2.76	2.47	25,634,880	56,653,085	53,397,455	14,163,271
United States	29,450,790	**72,718,000**	**56.0%**	16,479,819	40,722,080	**1.3**	0.76	**0.68**	0.99	**0.95**	16,330,907	38,685,976	34,017,279	9,671,494

Notes:

1. "Soybean Hectares Planted" by tillage system in Argentina is based on Qaim and Traxler, 2001 estimate that 70% Argentina soybean acreage is planted using no-tillage systems and 30% using conventional/conservation tillage. "Percent Hectares Planted to RR Soybeans" values are consistent with the Qaim and Traxler estimate that 90% of soybeans in Argentina were planted to RR varieties in 2000, and assume that conventional tillage systems are more common on farms planting conventional soybean varieties.

2. Percent U.S. acres planted to RR soybeans based on 62% of soybean acres treated with glyphosate herbicides in 2000 (USDA National Agricultural Statistics Service [NASS], 2001), assuming that 6% of those acres were conventional varieties planted with no-tillage systems, with glyphosate used as the burndown herbicide. The split between conventional/conservation tillage systems and no-till in the United States based on slight trend upward in no-tillage from 1998, when 72% of soybean acres were planted under conventional/conservation tillage and 28% under no-till (see Table 1.1 in *Troubled Times* (Benbrook, 2001).

3. Glyphosate sales in Argentina is 82.35 million liters of formulated commerical product with 480 grams per liter of glyphosate active ingredient, of which about 65% is for soybeans (53.5 million liters) (Qaim and Traxler, 2002). Average crop year rate of application on soybeans is (53.5 million liters divided by 9.288 million hectares planted, or 5.76 liters per hectare planted of formulated product, or 2.76 kilograms of glyphosate active ingredient per hectare of RR soybeans.

4. The sum of hectares/acres planted and kilograms/pounds applied across conventional/conservation tillage and no-till systems does not exactly equal the "All Tillage Systems" values because of rounding and conversion error.

5. Estimated glyphosate use on RR soybeans in the U.S. marginally exceeds USDA, NASS estimate because of assumption that all burndown applications on no-till acres planted to RR soybeans were made using glyphosate herbicides.

been aggressively marketed and priced competitively. As a result, U.S. farmers have been diversifying the mix of herbicide active ingredients applied on RR soybeans, whereas in Argentina, most farmers have intensified their use of glyphosate herbicides when and as problem weeds have emerged.

Both in the U.S. and Argentina, RR soybeans require more herbicides by volume than conventional soybeans, despite claims to the contrary by the biotechnology industry.

In the U.S. RR soybeans require 5 to 10 percent more herbicide active ingredient per acre. A May 2002 report is the latest official U.S. Department of Agriculture (USDA) document to present comparative data on herbicide use (Fernandez-Cornejo and McBride, 2002). Based on 1997 and 1998 survey data, the authors estimated that just less than 6 percent more herbicide was applied on RR varieties compared to conventional soybeans (measured as pounds of active ingredient applied per acre).

In Argentina, herbicide use on RR soybeans is more than double use on conventional varieties, although farmers planting conventional varieties use about one more tillage pass compared to farmers planting RR varieties (Table 3, Qaim and Traxler, 2002).

The impacts of GMOs other than RR soybeans on pesticide use have been mixed. Herbicide tolerant varieties of corn, cotton, and canola have reduced the number of herbicide active ingredients applied per acre in the U.S., while modestly increasing the pounds of herbicides applied per acre.

The impacts of *Bt* corn and cotton on insecticide use have varied across the U.S. *Bt* cotton has markedly reduced insecticide use in several states. The number of applications of organophosphate and carbamate insecticides has fallen from several to less than one per acre in several states. *Bt* corn, though, has had little if any impact on corn insecticide use.

2.3. Yield data

There is clear and consistent evidence in the U.S. that since introduction in 1996 most RR soybean cultivars produce 5 percent to 10 percent fewer bushels per hectare/acre in contrast to otherwise identical varieties grown under comparable field conditions. There is evidence that this “yield drag” has been reduced somewhat in recent years, as the Roundup tolerant trait has been moved into a broader diversity of varieties, offering farmers a better match to their soil type and maturity zone.

A team at the University of Nebraska estimated that the yield drag 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 published 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.

3. Environmental impacts of current practice

The adoption of the new technologies has had some desirable effects from an environmental standpoint. For one thing, there is a dramatic reduction in soil loss when highly erodible land is planted using no-till systems, leading to several unmistakable environmental benefits. And RR technology provides farmers new options for weed management in no-till systems. On highly erodible land planted to soybeans, no-till systems generally reduce soil erosion rates from 50 or more tons per acre to well under 10 tons, whereas on near-flat cropland, no-till reduces erosion only from two to five tons per acre to one to three tons.

The potential for no-till RR soybean systems to reduce erosion has largely gone unrealized in the U.S. because most no-till soybeans are planted on relatively flat, unerosive soils. Plus, since introduction of RR soybeans in the U.S., the percent of total acres planted using no-till has increased just three percent, from 30.5 percent in 1996 to 33.9 percent in 2000, according to a recent report issued by the Conservation Tillage Information Center.

The situation in Argentina appears quite different. No-till is used on a much larger share of total soybean acres. A credible estimate of the soil conservation benefits of no-till in Argentina would require information on the inherent erosion potential of hectares planted to no-till soybeans in Argentina, compared to land planted using conventional tillage. The benefits would be maximized if no-till planting systems are typically used in Argentina on the most highly erosive croplands

Also beneficial from an environmental standpoint may be the replacement of more toxic herbicides with glyphosate. A major advantage of RR soybean technology is that it allows farmers to reduce use of persistent, highly active low-dose herbicides in the sulfonylurea and imidazolinone families of chemistry. Most herbicides in these chemical families require careful management to avoid injury to soybean plants and reduced yields. Problems can also arise in subsequent rotational crops, given the persistence of several of these herbicides. Moreover, carry-over problems tend to be more frequent and serious in double cropping systems, such as those common in Argentina.

From an environmental perspective and in terms of farm income, the loss of the efficacy of glyphosate in managing corn-soybean weeds would be a disaster. Similarly the loss of *Bt* efficacy would foreclose one of the options of choice for low environmental impact.[3] Yet history shows us that excessive reliance on any single strategy of weed or insect management will fail in the long run, in the face of ecological and genetic responses.

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[3] While NGOs in the U.S. have focused on the need for managing resistance to *Bt*, because of the inherent safety and value of *Bt* biopesticides, the loss of the efficacy of glyphosate in managing corn-soybean weeds may well have a greater adverse impact on the environment and farmers than the loss of *Bt*.

Insects and weeds in farm fields have always and will forever find ways to adapt around the management technologies used against them. Three ecological responses have the potential to markedly undermine the RR soybean production system: shifts in the composition of weed species, the emergence of resistant weeds, and changes in soil microbial communities. (The serious threat of resistance has lead one major pesticide manufacturer to issue voluntary guidelines for U.S. farmers limiting the number of glyphosate applications in corn-soybean systems to just two over two years.[4])

Adaptation, whether in the form of shifts in the composition of weed and insect species or the emergence of genetic resistance, will impact the efficacy of GMO crops as a function of the degree of selection pressure directed against pest populations. While glyphosate-induced selection pressure against soybean weed populations in the United States has been high since 1998, it has been much higher in Argentina. In 2000, per hectare applications of glyphosate on RR soybeans in Argentina was about 2.76 kilograms, compared to about 1 kilogram in the U.S.

As such, soybean farmers in Argentina are placing weed populations under considerably greater selection pressure than farmers in the U.S. and they are doing it universally across essentially all land producing soybeans. If current adoption rates and herbicide use patterns prevail in both countries, it is likely that serious resistance, weed shifts, and agronomic problems will first emerge in Argentina.

Already the composition of weed species confronting farmers is clearly changing in both Argentina and the United States. Weeds that germinate over long periods of time find it easier to gain a foothold in RR fields, as do weeds with potential to grow tall with thick stems. Still, problems observed in the United States and also likely occurring in Argentina may prove manageable if farmers adopt routine, proven practices and strategies. Two key changes will be essential to keep RR soybean technology effective.

First, farmers must lessen reliance on it. Planting nearly all acreage to RR varieties will inevitably undermine the technology. Farmers in Argentina must back off their use of RR soybeans to perhaps no more than one-half planted acreage in any given year, if there is interest in sustaining the efficacy of this technology.

Second, weed management systems, practices, and technologies must be diversified. "Many little hammers" must be used in constantly changing combinations in order to keep weed problems from worsening year to year and to maintain the efficacy of weed management tools and technologies.

4. Emerging Issues Impacting the Performance of RR Soybean Cultivars

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[4] Syngenta issued voluntary guidelines for preserving the efficacy of glyphosate-based herbicides in February 2002. Access the guidelines at http://www.syngentacropprotection-us.com/enviro/ResistanceManagement/SyngentaGlyphosateesistanceManagementStrategy.pdf.

Much research has been carried out on aspects of the performance and impact of early GMO crops, in particular impacts on yield, pesticide use, gene flow, non-target organisms, the genetics and management of resistance to *Bt*, and economic returns to farmers. There is a considerable degree of consensus among most government and independent analysts on many often-debated topics including yield performance, pesticide use, and economic impacts on U.S. net farm income.

Other areas of research, however, are just getting underway. These include:

- Longer-term impacts on soil microbial communities and associated impacts on plant health.
- The stability of gene expression and the extent and consequences of transgene silencing.
- Impacts on plant defence mechanisms.
- Potential food safety hazards.

4.1. Impacts on soil microbial communities, plant health

Soil microbial population shifts will lead to complex, highly variable changes in the interactions between soil organisms, production systems, pests, and plants. The consequences may include reduced yields, new plant diseases, less tolerance of drought, and increases in the need for fertilizers or other production inputs.

Along these lines, research in the U.S. has found changes in soil microbial communities and plant health triggered by the application of glyphosate herbicide in Roundup Ready crops. Scientists have confirmed that Fusarium levels are increasing in some fields planted for multiple years to RR soybeans (Kremer et al., 2000). The adverse impact of the RR soybean system on soybean root development and nitrogen fixation had been documented in two peer-reviewed studies (King et al., 2001; Hoagland et al., 1999). Reports continue to surface in the Midwest of new and unusual problems with soybean diseases, as well as disease and physiological problems in corn planted in rotation with RR soybeans.

One set of problems is associated with elevated levels of Fusarium in corn harvested from fields previously planted to RR soybeans. Occurrences of psuedopregnancy, an occasional swine reproductive problem, have been linked to Fusarium contaminated corn on some hog farms direct-feeding harvested corn. The reason why some corn has unusually high Fusarium levels is under investigation. Some scientists suspect that the problem stems in some way from the buildup of Fusarium in fields following one or more years of RR soybean production. Roundup Ready corn may, under some circumstances, exacerbate the problem.

Scientists are exploring two plausible explanations for increased Fusarium levels in some RR soybean fields. First, plant root exudates following application of glyphosate may be providing an advantage to certain Fusarium strains relative to other fungi commonly found in midwestern soils. Second, applications of glyphosate may be directly impacting soil microbial communities in ways that provide a competitive advantage to certain Fusarium strains.

Impacts of RR technology on Fusarium-triggered diseases in plants and livestock warrant careful attention in the U.S. and Argentina. A team of university-based corn pest management experts in the U.S. recently analyzed the prevalence and severity of corn diseases. Fusarium-driven seedling, root and stalk rot was ranked the number one corn disease in terms of aggregate yield losses (Pike, 2002).

Fusarium graminearum fungi also trigger one of the most damaging diseases plaguing wheat farmers in the U.S. -- wheat scab, otherwise known as Fusarium head blight. This disease triggers losses in the U.S. on the order of $1 billion annually. Given the prevalence of wheat-soybean double-cropping in Argentina, the buildup of Fusarium species could lead to major impacts. The potential for Fusarium infection of wheat fields is obviously greater in such systems, especially those using no-till. This is because of the tendency of soil borne pathogens to reach higher levels in undisturbed soils. Wet conditions or moist locations in no-till fields are among the places and circumstances known to favor growth of certain fungi.

A second problem may emerge in Argentina from the impact of glyphosate applications on RR soybeans. A team at the University of Arkansas (King et al., 2001) has shown that RR soybean root development, nodulation and nitrogen fixation is impaired and that the effects are worse under conditions of drought stress, or in relatively infertile fields. While nitrogen is not often a limiting resource in soybean production in the U.S., this may not be the case in all parts of Argentina.

A portion of the land producing soybeans in Argentina is newly converted pastures and rangelands. Soil organic matter levels would, in all likelihood, be highest in the first few years after the beginning of intensive cultivation. But after such soils have been in production for three to five years, a reduction in organic matter levels and nitrogen (N) availability would be expected. Soil phosphorous (P) levels might also become a limited factor. If and as soil N and P levels decline in Argentina, the adverse impacts of glyphosate applications in RR soybean systems may become more pronounced, impacting a greater percentage of the planted area and reducing yields and increasing fertilization costs more sharply than the case to date.

U.S. research has shown that yields can fall up to 25 percent in the RR plots treated with glyphosate compared to conventional controls (King et al., 2001). Other things being equal,

- The more intense the use of glyphosate, the greater the likely impact on root development and nitrogen fixation.
- Drought stress is likely to worsen adverse impacts on root development and N fixation.

- The greater the reduction in root development and N fixation, the more vulnerable the plant to stress-induced yield losses compared to well managed conventional soybeans with healthy root systems and normal N fixation.

4.2. Plant physiology, defense mechanisms

Questions have arisen in the U.S. over the physiological performance and responses of RR soybean cultivars to various sources of stress and growing conditions. Monsanto studies have shown minor depression of aromatic amino acid levels in harvested RR soybeans, including the key plant regulatory compounds phenylalanine and trypsin. Even modestly depressed levels of key regulatory proteins at the end of the season may be important indicators of earlier problems, since levels may have been depressed more significantly earlier in the season, but later recovered.

Short-term depression in the levels of these aromatic compounds might erode crop yields because of early-season pest pressure and damage. The absence of normal levels of aromatic amino acids may delay and/or mute the RR soybean immune response, opening a window of opportunity for soil-borne pathogens and other pests. As a result, plants will have to invest additional energy over an extended period to combat pests or overcome stress. In some fields, the diverted energy can impose an irreversible yield penalty on plants, despite full or near-full recovery prior to harvest in aromatic amino acid levels.

5. Conclusions

The food and agricultural system in Argentina is heavily dependent on the current and future performance and acceptability of Roundup Ready soybeans. Ample evidence has emerged in the U.S. to point to the need for proactive measures in both the U.S. and Argentina to lessen the chance that serious problems will emerge. Weed shifts and resistance to glyphosate are already beginning to appear and if not managed, could undermine the profitability of the technology within as few as five years. The targeting of future RR soybean plantings to problem-fields, as determined via weed population thresholds, would be consistent with the principles of Integrated Pest Management and would slow the pace of weed shifts and markedly lessen the risk of resistance.

If and as RR soybean systems fail in Argentina, alternative soybean weed management technology in Argentina will almost certainly be more heavily dependent on tillage and on herbicides other than glyphosate. Costs will surely rise, and the environmental impacts of soybean weed management will likely worsen. Minimizing the adverse consequences of change in soybean weed management will require proactive diversification of methods, practices, and systems before problems become widespread and severe. There is good reason to predict that thoughtful and disciplined action can largely sustain the sizable benefits of RR soybean technology in Argentina. But achieving this goal will require a high level of adherence to sound, well-proven pest management principles.

Introduction

This paper brings together a wide reading of the current agricultural research on genetically modified organisms, and data on planting, use rates and yields, focusing specifically on three crops: Roundup Ready (RR) soy, *Bt* cotton, and *Bt* corn. With a view to drawing out the implications for crop management strategies in the U.S. and Argentina—the two biggest users of the new technologies—it first looks at rates of adoption, herbicide use rates and yield data.

It then looks at the environmental effects of current practice. Those effects include several pieces of environmental good news, including benefits to soil conservation from new cropping techniques, and the benefits of using glyphosate in combination with RR soy, replacing more toxic and persistent herbicides. But they also include some worrying news. Poor management of the new technologies risks undermining their effectiveness, as selection pressures lead to weed and pest shifts, and to increased resistance. The study predicts that with Argentine levels and patterns of use, these problems should be surfacing soon, if they are not already.

The study also looks at emerging issues that may impact the performance of RR soybean cultivars. New research shows that the process of making soy cultivars Roundup Ready may also impair their physiological performance under certain types of stress and growing conditions. Other research looks at the changes in soil microbial communities that are brought about by high levels of glyphosate use. Particularly worrying are the observed links between glyphosate use and increased levels of Fusarium – a fungus associated with a number of crop and livestock diseases. Also worrying are the observed negative effects of glyphosate on soybean root development and nitrogen fixation.

I. Impacts of Herbicide Tolerant and Insect Tolerant Crops on Pesticide Use

In the United States, herbicides tolerant varieties have modestly reduced the average number of active ingredients applied per hectare/acre but have modestly increased the average pounds applied per hectare/acre. This is because most herbicide tolerant varieties are resistant to glyphosate herbicide, an active ingredient that is applied at a moderate-to-high dose, compared to other commonly used soybean and corn herbicides.

The slight shifts in hectare/acre-treatments and pounds applied per hectare/acre are of little practical significance. Moreover, in general glyphosate has a more favorably environmental profile than most soybean herbicides it has displaced. In particular, glyphosate poses far less risk per hectare/acre treated than paraquat, another burndown herbicide used pre- or at planting in not-till systems.

Why then the ongoing, often acrimonious debate in the U.S. over the impact of RR soybeans on pesticide use? Debate in the U.S. was triggered by and persists because of claims by the biotechnology industry, farm groups and proponents of biotechnology that

RR soybeans actually have reduced herbicide use on the order of 20 percent to 30 percent. These claims are false and can be traced to Monsanto-funded, proprietary studies employing biased analytical methods, as documented below.

The impact of *Bt* corn and cotton on insecticide use is mixed. *Bt* cotton has reduced insecticide use in several states, whereas *Bt* corn has had little if any impacts on corn insecticide use. From an environmental perspective in the U.S., *Bt* cotton is the only legitimate "success story" among today's GMO crop varieties.

A. Herbicide Use in U.S. Soybean and Corn Production

Corn herbicides account for about 40 percent of the total pounds of herbicides, insecticides, and fungicides that are applied annually by U.S. farmers (Table 3.2, Economic Research Service [ERS], 1997). Soybean weed management is the second biggest market, accounting for about 68 million pounds applied annually.

1. Impacts of Herbicide-Tolerant Soybeans on Herbicide Use

Five years of USDA soybean herbicide use data (1997-2001) are available and support four conclusions:

- Slightly more pounds of herbicides are applied on the average hectare/acre of RR soybeans compared to the average hectare/acre planted to conventional soybean varieties.
- Fewer herbicide active ingredients are applied on the average hectare/acre of RR soybeans relative to the average conventional hectare/acre.
- Average per hectare/acre pounds of herbicide applied on RR soybeans exceeds by two to ten-fold herbicide use on the approximate 30 percent of soybean hectares/acres where farmers depend largely on low-dose imidazolinone and sulfonylurea herbicides.
- Total herbicide use on RR soybean hectares/acres is gradually rising as a result of weed shifts, late-season weed escapes leading to a buildup in weed seedbanks, and the loss of susceptibility to glyphosate in some weed species (Hartzler, 1999; HRAC, 2001).

While RR soybean technology has not reduced herbicide use measured by pounds applied in either the U.S. or Argentina, it has made possible a shift toward a generally benign herbicide in terms of mammalian risks and ecotoxicity. The shift has lessened carryover and phytotoxicity problems stemming from soybean herbicide use, and it certainly has been a remarkable commercial success. Farmers in both countries have embraced the technology because it greatly simplifies soybean weed management and provides additional degrees of freedom in managing weeds (Benbrook, 2001a; Gianessi and Carpenter, 2000; ERS, 1999). Figure 1 contrasts the rate of adoption of herbicide tolerant varieties in the U.S. and Argentina.

The faster and more extensive adoption in Argentina has been driven, no doubt, by greater economic advantages. On average in the U.S., RR soybeans have been an economic wash – the increased cost of seed has about equaled the reduction in herbicide expenditures, whereas in Argentina, RR technology has clearly cut costs compared to conventional soybean production systems. Two factors drive this outcome.

First, farmers in Argentina have the unrestricted ability to save seed. According to Qaim and Traxler (2002), only about 30 percent of soybean seed is purchased annually in Argentina. Plus, the seed premium for RR soybeans that are purchased is less than half the premium in the U.S.

The relative cost of glyphosate herbicides is the second factor accounting for the greater economic advantage of the RR system in Argentina compared to the U.S. The price of a hectare/acre-treatment with glyphosate herbicide has declined in the U.S. from about \$10.00 to \$12.00 in 1996 to \$7.00 to \$8.00 in 2001, or by about one-third. The price of glyphosate has declined from \$5.63 per liter of formulated product (48 percent glyphosate) in 1995/96 to \$2.67 in 2000/01 in Argentina, over a 50 percent drop (Qaim and Traxler, 2002).

Problems with alternative sulfonylurea and imidazolinone-based weed management systems in the U.S. have also contributed to the popularity of the RR system. These include high costs; control problems; a long and growing list of resistant weeds; and, a tendency to trigger crop damage if not applied with considerable care and precision (Fernandez-Cornejo and McBride, 2000 and 2002; Gianessi and Carpenter, 2000). RR soybeans are especially popular and beneficial on fields where weeds have proven tough to manage and/or have gotten out of control as a result of poor management (Gunsolus et al., 2001). The targeting of future plantings to problem-fields, as determined via weed population thresholds, would be consistent with the principles of Integrated Pest Management (IPM) and would slow the pace of weed shifts and markedly lessen the risk of resistance.

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 0.0045 kg/hectare to 0.14 kg/hectare (0.004 to 0.125 pounds per acre) of active ingredient (page 44, Gianessi and Carpenter, 2000). The typical glyphosate application rate of 1.5 pints is equivalent to 0.84 kg/hectare (0.75 pound/acre), or six-fold to almost two hundred times greater than the rate of alternative herbicides.

Each year the U.S. Department of Agriculture's National Agricultural Statistics Service (NASS) carries out a field crop pesticide use survey. Soybean herbicide use data are collected and reported by state and summarized nationally. Data reported include percent hectares/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 hectares/hectares/acres in a state are included in the reports.

Of the 34-herbicide active ingredients applied to 1 percent of more of national soybean hectares/acres in 1999, there were 13 applied at an average rate less than 0.112 kg/hectare (0.1 pounds/acre). Just five were applied at rates equal to or greater than 1.12 kg/hectare (1.0 pound/acre). USDA's pesticide use data also show that the average rate of glyphosate per crop year was 1.03 kg/hectare (0.92 pounds/acre) of active ingredient. About 30 percent of the hectares/acres treated with glyphosate received two Roundup applications.

Trends in soybean herbicide use in pounds per acre, based on annual USDA survey data, appear in Table 2. Tables 3 and 4 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 hectares/acres treated, about 87 percent.

Table 2. 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).

No Glyphosate Applied			
Percent Acres Treated	96.1%	95.7%	62.2%
Average Number of Herbicides Applied	2.2	2.5	2.5
Total Pounds Active Ingredient Applied	1.11	1.01	1.07
Non-GMO Soybeans	N/A	N/A	1.08
Glyphosate Applied			
Percent Acres Treated	3.9%	4.3%	37.8%
Average Number of Herbicides Applied	3.6	3.9	1.4
Average Rate of Glyphosate Applied	0.56	0.56	0.92
Non-GMO Soybeans	N/A	N/A	0.68
Total Pounds Active Ingredient Applied	1.59	1.63	1.16

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).

Table 3 presents these data on fields managed with conventional/ conservation tillage and Table 4 covers land planted using no-tillage systems. 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, a finding confirmed in recent private (Gianessi and Carpenter, 2000) and USDA analyses (Fernandez-Cornejo and McBride, 2002).

Table 3. 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).

Table 4. 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).

An updated study of the impacts of herbicide tolerant crops in the U.S. on conservation tillage estimates that most of the growth in no-till in the U.S. since 1996 has occurred as a result of the availability of herbicide-tolerant varieties (Fawcett and Towery, 2002). In 2002 according to the report, 6.1 million hectares (15 million acres) of corn were planted using no-till systems and 10.5 million hectares of soybeans (26 million acres). A range of benefits of conservation and no-till systems are reviewed including lessened erosion and sedimentation of water ways, improved soil quality, less fuel and labor use, and better wildlife habitat. A survey of soybean growers found that 1.8 fewer tillage passes were made in 2001 compared to 1996, with most of the decrease attributed to RR soybeans. The report does not discuss impacts on herbicide use rates, weed shifts, net returns to farmers, or the need to manage resistance.

Distribution of Herbicide Rates

Field-level soybean herbicide use data collected by the USDA's National Agricultural Statistics Service in 1998 was used to assess the distribution of herbicide application rates from those farms using the least herbicide to those applying the most. This analysis was carried out through a series of special tabulations run by the USDA's Economic Research Service for Benbrook Consulting Services. The tabulations encompassed herbicide use on all soybean acres, acres planted to conventional varieties, acres planted to RR soybeans, as well as all acres broken into conventional/conservation tillage acres versus no-till acreage.

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. (For more methodological details, see Benbrook, 2001a).

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 5 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 and surveyed by NASS. At the high end of the distribution, 10 percent of acres were treated with 1.98 or more pounds (2.22 kg/hectare). 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 (1.27 kg/hectare).

Table 5. 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).

At the low-end of the distribution, 10 percent of soybean hectares/acres under conventional tillage were treated with 0.058 pounds or less of herbicide (0.065 kg/hectare), 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 hectare/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 6 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 pre-plant application of herbicide.

Table 6. 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 5 and 6, 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 (1.68 kg/hectare), 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.

Table 7 and 8 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 7 and 8 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.

Table 7. 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 8. 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).

For conventional/conservation tillage soybeans, the ratios in Table 7 fall from 34 to 3 to 1.7 in comparing the top 10th decile to the bottom 10th, the top 20th to the bottom 20th, and the top 30th to bottom 30th. 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 8) compared to conventional/conservation tillage. Still, 7.5 times or more herbicide are used in the top decile compared to the bottom and twice or more in the 70th decile compared to the 30th.

2. Corn Weed Management

Corn producers rely predominantly on herbicides in managing weeds. Since 1971 the number of distinct herbicide active ingredients applied on the average hectare/acre of corn in the U.S. has risen from 1.09 active ingredients to 1.75 in 1982 and 1.98 in 1991 (NASS, multiple years). The trend continued gradually upward throughout the 1990s and reached 2.7 herbicides in crop year 2000.

The dominant corn herbicides have changed little throughout this period, measured either by percent hectares/acres treated or pounds applied. Each year atrazine has alone accounted for about 30 percent of all corn herbicide hectares/acres treated and about 35 percent of kilograms/pounds applied, as shown in Appendix Tables 3 (acres treated) and 4 (pounds applied). The acetanilide herbicides alachlor (largely replaced by acetochlor in 1994-1995 in the U.S.) and metolachlor (replaced by S-metolachlor in 1998-2000) have together accounted for another approximate 30 percent of total hectares/acres treated and over 40 percent of pounds applied.

The average pounds of herbicides applied to corn peaked in 1982 at almost 3 pounds per acre (3.36 kg/hectare) and hovered in the 2.6 to 2.8 pounds range from 1991 through 1997 (2.9 to 3.1 kg/hectare). The first significant reduction in pounds applied occurred in 1998, when rates dropped from 2.63 pounds per acre to 2.47 pounds, according to USDA/NASS pesticide use data.

Roundup Ready (RR) corn hit the market in 1997. There are no accurate public sources of data on the hectares/acres planted to RR corn. A rough estimate of hectares/acres planted can be inferred from review of USDA corn pesticide use data. Assuming no-till usage of glyphosate remained the same in 1999-2001 as it had been in previous years, USDA data suggests that 5 to 7 percent of corn acres have been planted to Roundup Ready corn varieties.

Monsanto's recommended RR corn systems include several optional herbicide programs ranging from a total-glyphosate system, to systems combining a pre- or at-plant residual herbicide followed by Roundup post-emergence, or a total post-emergence program involving applications of a residual post-product plus Roundup (Monsanto, 2000a and 2000b). In the total Roundup program, glyphosate is applied on average about twice. In 1999 the average application was about 0.7 pounds per acre (0.78 kg/hectare), resulting in 1.4 pounds of Roundup applied on the average acre of RR corn.

An estimated 70 percent of RR corn hectares/acres were managed under the "Residual Herbicide Applied" program. Either before or at-planting in such programs, farmers apply a tank-mix containing a residual broadleaf product like atrazine at about .8 pounds per acre, plus an acetanilide herbicide at a rate of about 1.2 pounds per acre on average, mostly for grass weed control (see recommended rates on either Roundup labels or the labels of several herbicide products containing mixtures of atrazine and an acetanilide).

Total corn herbicide use under the "Residual Herbicide Applied" program averages about 2.75 pounds per acre (3.1 kg/hectare), with Roundup accounting for 0.75 pounds of this total. On acres planted to non-GMO varieties, about 2.25 pounds of herbicides are applied on average. Accordingly, the average RR corn hectare/acre is treated with about 20 percent more herbicide than the average non-GM corn hectare/acre.

B. Impacts of *Bt*-transgenic Crops on Insecticide Use

Bt-transgenic technology uses a natural plant toxin and a novel delivery system to mimic chemical-based pest management systems. In a given crop and region, the impacts of *Bt*-varieties on insecticide use are complex and changeable.

In the case of *Bt*-corn, USDA pesticide use data show that corn insecticide applications directly targeting the European corn borer (ECB) have risen from 4 percent of hectares/acres treated in 1995 to 5 percent in 2001, as shown in Table 9. In addition, several other insecticides are applied that control both the ECB and corn rootworm complex. A portion of these treated hectares/acres must therefore be counted as part of ECB-driven insecticide use (EPA Benefits Assessment, 2000); in Table 9, 25 percent of the "Multiple Pests" applications are assumed to target the ECB and 50 percent, corn rootworms.

A total of about 6.9 percent of corn hectares/acres were treated for ECB control in 2001, down from 8.1 percent in 1999. Corn insecticide use targeting all insect pests has remained steady in the 1990s at about one-third of corn hectares/acres planted, as shown in the bottom line in Table 9.

Bt-cotton, on the other hand, has reduced insecticide use markedly in several states. Close to half cotton insecticide acre-treatments either solely or partially target the budworm-bollworm (BBW) complex of insects, the target of *Bt* cotton. The average cotton acre received 2.21 acre-treatments with insecticides targeting the BBW complex in 1992. Reliance peaked in 1995 at just over 3 acre-treatments per acre and has fallen to just 0.77 in 2000, as shown in Table 9.

Table 9. Percent of U.S. National Corn Acres Treated with Insecticides by Target Pest and All Pests (Assumes One-Quarter of "Multiple Pests" Applications Target the ECB, One-Half Target Corn Rootworms, and One-Quarter Target Other Insects)

Active Ingredient	Likely Target Pest	1971	1982	1991	1995	1998	1999	2000	2001
lambda-cyhalothrin	ECB					2.00	3.00	2.00	2.00
permethrin	ECB			2.00	4.00	2.00	3.00	3.00	3.00
carbaryl	ECB	1.62	0.17						
diazinon	ECB	2.50	0.18	0.20					
malathion	ECB	0.20							
methomyl	ECB		0.40						
methoxychlor	ECB	0.08							
Subtotal ECB Control		**4.4**	**0.8**	**2.2**	**4.0**	**4.0**	**6.0**	**5.0**	**5.0**
One-Quarter of Acreage Treated for "Multiple Pests"		0.7	1.2	3.0	2.8	2.5	2.1	2.3	1.9
Total Acreage Treated for ECB		**5.1**	**2.0**	**5.2**	**6.8**	**6.5**	**8.1**	**7.3**	**6.9**
terbufos	Rootworm		9.40	8.00	6.00	6.00	5.00	3.00	3.00
tefluthrin	Rootworm			2.00	5.00	5.00	7.00	7.00	6.00
cyfluthrin	Rootworm					3.00	2.00	2.00	4.00
tebupirimiphos	Rootworm					3.00	2.00	2.00	4.00
carbofuran	Rootworm	4.97	6.66	3.00	2.00	1.00	1.00	0.10	0.10
chlorethoxyfos	Rootworm					1.00	1.00	0.10	
fonofos	Rootworm		6.88	4.00	1.00	1.00			
phorate	Rootworm	4.53	4.57	2.00	1.00	0.28		0.10	0.10
fipronil	Rootworm					1.00	1.00	4.00	3.00
aldrin	Rootworm	10.18							
bufencarb (RE-5353)	Rootworm	5.98							
chlordane	Rootworm	0.72							
DDT	Rootworm	0.01							
endrin	Rootworm	0.10							
ethoprophos	Rootworm		0.84						
flucythrinate	Rootworm			0.15					
heptachlor	Rootworm	2.57							
isofenphos	Rootworm		1.15						
paraquat dichloride	Rootworm		0.25						
toxaphene	Rootworm	0.19	0.37						
trimethacarb	Rootworm			0.17					
Subtotal Rootworm		**29.2**	**30.1**	**19.3**	**15.0**	**21.3**	**19.0**	**18.3**	**20.2**
One-Half of Acreage Treated for "Multiple Pests"		1.4	2.5	6.0	5.5	5.0	4.1	4.6	3.7
Total Acreage Treated for Rootworm		**30.6**	**32.6**	**25.4**	**20.5**	**26.3**	**23.1**	**22.9**	**23.9**
chlorpyrifos	Multiple Pests		4.13	9.00	7.00	6.00	5.00	6.00	4.00
bifenthrin	Multiple Pests			0.34	1.00	2.00	2.00	2.00	2.00
fenvalerate	Multiple Pests		0.07						
esfenvalerate	Multiple Pests			0.44			0.15	0.10	0.10
dimethoate	Multiple Pests		0.00	0.28		1.00	0.11	0.30	0.30
parathion-methyl	Multiple Pests	0.06	0.19	2.00	3.00	1.00	1.00	0.70	1.00
disulfoton	Multiple Pests	0.70	0.01						
monocrotophos	Multiple Pests		0.07						
oxydemeton-methyl	Multiple Pests		0.47						
parathion	Multiple Pests	2.06							
Subtotal Products Applied for "Multiple Pests"		**2.8**	**4.9**	**12.1**	**11.0**	**10.0**	**8.3**	**9.1**	**7.4**
Total Acres Treated (All Insect Pests)		**36.4**	**35.8**	**33.6**	**30.0**	**35.3**	**33.3**	**32.4**	**32.6**

Source: Compiled by Benbrook Consulting Services, based on data in USDA/NASS field crop chemical use surveys, multiple years.

In terms of pounds applied, insecticide use targeting the BBW complex has fallen from about one-half pound per acre in the early 1990s to 0.28 pounds per acre in 2000. Two factors clearly account for this large reduction – the boll weevil eradication program and second, *Bt* cotton, especially in the western U.S.

Cotton insecticide use trends must be studied carefully to accurately identify cause-effect relationships. The biggest reductions in bollworm-budworm complex insecticide use have occurred in the use of methyl parathion, profenofos, and thiodicarb. The former two are highly toxic organophosphates (OPs) that have triggered resistance problems and regulatory restrictions. As a result, most of the reduction in their use had occurred by the end of the 1996 season, prior to widespread use of *Bt*-cotton.

In some high adoption states, especially Arizona, BBW applications have fallen dramatically from over 3 acre-treatments per acre in 1994 to just 0.1 in 2000 (state level data are contained in the September 20, 2001 comments by the Union of Concerned Scientists on the EPA's *Bt* cotton benefits assessment, accessible at http://www.biotech-info.net/*Bt*_rereg.html). Remarkably, only 2,000 pounds of BBW complex insecticides were applied in 2000 in Arizona, down from 397,000 in 1995. Much of this decline is likely attributable to *Bt* cotton, which was planted on over 75 percent of acres-planted (revised EPA benefits assessment, Table E.8).

But in Alabama, another high *Bt*-cotton adoption state (62 percent acres planted), BBW insecticide applications almost doubled from 1997 to 2000. Moreover, there was a clear shift in Alabama toward very toxic, broad-spectrum materials. Similar dramatic changes have occurred in Mississippi cotton insect pest management. In the first half of the 1990s, cotton farmers made eight to nine applications per acre targeting the BBW complex, with the highly-toxic OP methyl parathion accounting for over 40 percent of acre-treatments and pounds applied. *Bt* cotton has helped Mississippi growers reduce BBW insecticide acre-treatments from 9.4 in 1995 to just under 0.6 in 2000. Pounds applied fell from 2.8 pounds to 0.2 pounds per acre.

But some low-adoption *Bt*-cotton states also markedly reduced BBW acre-treatments. Texas cotton (7 percent *Bt*-cotton), for example, was treated an average 1.3 times with BBW insecticides in 1995 and 0.65 times in 2000 – a 50 percent drop.

Lessons learned from five-decades of insecticide-based cotton pest management in the United States are relevant in assessing the likely longer-run impacts of insect resistance GM crops on pesticide use both in the U.S. and Argentina.

Worldwide, three major families of chemistry have accounted for most cotton insecticide use from the 1960s through 1980s -- the organochlorines, or chlorinated hydrocarbons (DDT, aldrin/dieldrin, toxaphene, chlordane/heptachlor); the organophosphates (parathion, malathion, chlorpyrifos, among many others); and carbamates (aldicarb, carbofuran, carbaryl, oxamyl). In the mid-1980s the synthetic pyrethroids came into use (permethrin, cypermethrin, esfenvalerate). Changes in reliance across families of chemistry in the U.S. are shown in Table 10.

Table 10. National Cotton Insecticide Acre Treatments by Likely Target Pest Category

Likely Target Pest	1992	1993	1994	1995	1996	1997	1998	1999	2000
Budworm/Bollworm Complex									
aldicarb	1,010,000	1,111,000	1,650,000	1,755,000	2,499,000	3,537,000	2,640,000	3,857,000	3,744,000
azinphos-methyl	2,302,800	2,626,000	2,160,000	2,152,800	1,356,600	1,310,000	384,000	798,000	489,600
Bt	1,262,500	1,535,200	2,340,000	3,474,900	785,400	419,200	204,000	186,200	230,400
Carbofuran			520,000	1,228,500	714,000	393,000	600,000	665,000	720,000
cyfluthrin	2,110,900	1,818,000	2,640,000	3,931,200	2,618,000	2,895,100	3,024,000	1,702,400	1,497,600
Cypermethrin	1,454,400	767,600	840,000	1,579,500	1,820,700	1,781,600	2,100,000	665,000	1,267,200
Emamectin benzoate									345,600
fenpropathrin		181,800	560,000	772,200		144,100	33,333	16,625	77,778
Indoxacarb									432,000
parathion-ethyl	282,800								
parathion-methyl	7,201,300	10,463,600	12,880,000	11,863,800	7,235,200	4,598,100	3,672,000	2,340,800	1,512,000
profenofos	2,727,000	2,302,800	3,300,000	3,194,100	952,000	838,400	720,000	518,700	172,800
tebufenozide				608,400					288,000
thiodicarb	1,818,000	2,444,200	2,070,000	3,229,200	952,000	786,000	384,000	93,100	50,000
tralomethrin	1,212,000	1,414,000	1,000,000	1,638,000	642,600	550,200	204,000	518,700	316,800
Subtotal	**21,381,700**	**24,664,200**	**29,960,000**	**35,427,600**	**19,575,500**	**17,252,700**	**13,965,333**	**11,361,525**	**11,143,778**
Acre-treatments per planted acre	**2.12**	**2.44**	**3.00**	**3.03**	**1.65**	**1.32**	**1.16**	**0.85**	**0.77**
Multiple Pests									
acephate	1,636,200	1,545,300	2,400,000	3,112,200	2,284,800	2,227,000	2,244,000	2,793,000	2,592,000
bifenthrin	656,500	505,000	700,000	1,053,000	119,000		66,667	266,000	345,600
chlorpyrifos	1,060,500	1,818,000	1,260,000	2,106,000	952,000	995,600	576,000	172,900	1,080,000
endosulfan	242,400	282,800	440,000	807,300	535,500	602,600	360,000	399,000	403,200
malathion	262,600		660,000	2,457,000	4,652,900	8,501,900	8,184,000	36,176,000	35,769,600
methamidophos	222,200	101,000		304,200		183,400	60,465	20,482	288,000
methomyl	1,201,900	1,272,600	960,000	2,000,700	333,200	445,400	288,000	124,355	144,000
permethrin	212,100				154,700		120,000	11,970	25,000
Subtotal	**5,494,400**	**5,524,700**	**6,420,000**	**11,840,400**	**9,032,100**	**12,955,900**	**11,899,132**	**39,963,707**	**40,647,400**

Acre-treatments per planted acre	**0.54**	**0.55**	**0.64**	**1.01**	**0.76**	**0.99**	**0.99**	**3.00**	**2.82**
Other									
abamectin	333,300	303,000	480,000	982,800	654,500	576,400	288,000	266,000	432,000
amitraz	101,000		510,000	748,800	333,200	157,200	13,636		79,310
chlorfenapyr							264,000		
dicofol	505,000	505,000	660,000	386,100	523,600	262,000	132,000	266,000	144,000
dicrotophos	1,838,200	1,969,500	2,160,000	2,106,000	1,701,700	1,781,600	1,152,000	2,074,800	1,612,800
diflubenzuron				1,123,200			144,000		21,429
naled			220,000	351,000		288,200	19,767	71,820	53,191
petroleum oils							144,000		
propargite	343,400		200,000	234,000	238,000	144,100	43,506	35,910	48,760
sulfur									31,933
Subtotal	**3,120,900**	**2,777,500**	**4,230,000**	**5,931,900**	**3,451,000**	**3,209,500**	**2,200,910**	**2,714,530**	**2,423,424**
Acre-treatments per planted acre	**0.31**	**0.28**	**0.42**	**0.51**	**0.29**	**0.25**	**0.18**	**0.20**	**0.17**
Whitefly / Thrips									
buprofezin					48,571	45,714	31,429		27,273
deltamethrin					190,400	746,700	900,000	186,200	432,000
dimethoate	1,131,200	1,292,800	650,000	842,400	499,800	340,600	312,000	518,700	316,800
disulfoton			500,000	514,800	595,000	524,000	600,000	532,000	144,000
esfenvalerate	1,616,000	929,200	1,150,000	1,556,100	1,166,200	1,048,000	540,000	266,000	125,000
imidacloprid				1,368,900	1,082,900	1,021,800	624,000	558,600	475,200
lambda-cyhalothrin	3,555,200	2,545,200	5,800,000	5,405,400	3,998,400	4,480,200	4,560,000	2,128,000	1,944,000
oxamyl	1,777,600	1,616,000	2,080,000	2,433,600	2,320,500	3,144,000	2,112,000	2,606,800	2,851,200
phorate	303,000	404,000	600,000	585,000	476,000	917,000	600,000	532,000	720,000
pyriproxyfen					142,800	131,000	120,000	39,900	60,000
spinosad							768,000	478,800	1,368,000
sulprofos	686,800		560,000	280,800			12,698		
zeta-cypermethrin		363,600	1,470,000	2,527,200	761,600	917,000	1,380,000	798,000	648,000
Subtotal	**9,069,800**	**7,150,800**	**12,810,000**	**15,514,200**	**11,282,171**	**13,316,014**	**12,560,127**	**8,645,000**	**9,111,473**
Acre-treatments per planted acre	**0.90**	**0.71**	**1.28**	**1.33**	**0.95**	**1.02**	**1.05**	**0.65**	**0.63**
Total all insects	**39,066,800**	**40,117,200**	**53,420,000**	**68,714,100**	**43,340,771**	**46,734,114**	**40,625,502**	**62,684,762**	**63,326,074**
All Acre Treamtments per planted acre	**3.87**	**3.97**	**5.34**	**5.87**	**3.64**	**3.57**	**3.39**	**4.71**	**4.40**

Resistance began driving down the use of chlorinated hydrocarbons (OCs) in the U.S. in the mid-1960s. In the late 1970s, use of this family of chemistry collapsed and now accounts for a trivial share of total U.S. cotton insecticide use.

The collapse of the OCs coincided with the introduction of the OPs and carbamates. OPs and carbamates are applied at lower rates (0.3 to 0.8 pounds a.i. per acre; 0.336 to 0.9 kg/hectare) compared to the OCs (1.0 to 1.5 pounds per application). Still, multiple annual applications of the OPs and carbamates have added up to significant pounds and major environmental impacts.

OP and carbamate pounds applied doubled from the mid-1960s to the mid-1970s. Heavy use brought on resistance quickly, leading to the collapse in OP and carbamate use from 1976 to 1982. The huge spike in OP use in 2000 was caused by the approximate 24 million pound (10.9 million kilograms) increase in malathion use in USDA-sponsored boll weevil eradication programs.

The "pesticide treadmill" cycle began anew in the late 1970s as resistance eroded OP/carbamate efficacy, an event that coincided with the introduction of the synthetic pyrethroids. These insecticides are applied at even lower rates – from 0.03 to 0.2 pounds per application per acre (0.0336 to 0.224 kg/hectare). Hence, the total synthetic pyrethroid pounds applied appear modest in Table 10, when in fact this family of chemistry now accounts for nearly as many acre-treatments as the OPs (not counting the 35.6 million acre-treatments of malathion in 2000).

The introduction of the synthetic pyrethroids in the 1980s gave cotton farmers a badly needed new family of chemistry to rotate with the OPs and carbamates. The same can be said of the registration of *Bt*-cotton in 1996.

The OC, OP, carbamate and synthetic pyrethroid boom-to-bust cycles each lasted about a decade. Despite today's *Bt*-crop insect resistance management (IRM) plans, resistance is likely to emerge about as quickly in regions where *Bt* crops are planted extensively. The reason why was explained in a seminal article in the *Proceedings of the National Academy of Sciences* entitled "A Total System Approach to Sustainable Pest Management" (Lewis et al., 1997):

> "Genetic engineering and other such technologies are powerful tools of great value in pest management. But, if their deployment is to be sustainable, they must be used in conjunction with a solid appreciation of multitrophic interactions and in ways that anticipate countermoves within the systems. Otherwise, their effectiveness is prone to neutralization by resistance in the same manner as pesticides." (Lewis et al., 1997).

Lewis and co-authors argue that the central problem plaguing pest management has been failure to recognize the need – and opportunities – to manage natural plant-best-beneficial interactions, and that any toxin-based intervention will be met by "countermoves that 'neutralize' their effectiveness." (Lewis et al., 1997). They highlight a key lesson from five decades of recurrent pest management crises in cotton production:

> "The use of therapeutic tools, whether biological, chemical, or physical, as the primary means of controlling pests rather than as occasional supplements to natural regulators to bring them into acceptable bounds violates fundamental unifying principles and cannot be sustainable." (Lewis et al., 1997).

Similar concerns apply to herbicide tolerant and *Bt*-transgenic varieties, especially in areas with high levels of adoption. Both technologies simplify pest management systems and hence are prone to the "countermeasures" highlighted by Lewis et al.

II. Sustaining the Benefits of GMOs Crops

The evolution of weed management technology has shown over and over 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, corn, and cotton systems are no exception.

Likewise, heavy reliance on one or a few insect pest management methods, especially one or a few insecticides, also invariably triggers ecological responses that eventually undermine efficacy (Lewis et al., 1997). The capacity of insects to develop resistance to synthetic chemical or bacterial toxins has led the U.S. Environmental Protection Agency (EPA) to place great emphasis on the management of resistance in target pests to *Bt* toxins. EPA requirements have, in turn, triggered much research on the genetics of resistance to *Bt* in target pests and on whether and how resistance can be managed.

Public interest groups have highlighted the importance of foliar *Bt* insecticides to fruit and vegetable producers in arguing that the goal of *Bt* corn and cotton resistance management plans (RMPs) must be ***prevention*** of resistance from gaining a stable foothold in pest populations. Biotechnology industry representatives have argued that *Bt*-crop resistance management plans should not be held to a higher standard than RMPs applicable to chemical insecticides and that a plan should be considered effective if it has potential to delay the emergence of resistance by 10 to 20 years. It remains to be scene how effective today's *Bt*-crop RMPs will prove to be and what the EPA will do if and when evidence of resistance emerges. It is doubtful, however, that the response will be quick enough or decisive enough to reverse the spread of resistance genes in target pest populations (for reasons why, see Benbrook, 1999).

While NGOs in the U.S. have focused on the need for managing resistance to *Bt*, because of the inherent safety and value of *Bt* biopesticides, a similar case can be made for preserving the efficacy of glyphosate, which is among the safest herbicides currently on the market. As a practical matter, the loss of the efficacy of glyphosate in managing corn-soybean weeds will likely have a far greater adverse impact on the environment and farmers than the loss of *Bt* in the wake of resistance.

A. Weed Shifts and Resistance

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). In general, weeds capable of germinating continuously for most of the season pose greater problems than weeds that germinate in relatively tight windows. Waterhemp, velvetleaf, horseweed, yellow nutsedge and nightshade are more common and difficult to control, especially in RR fields, in large part because they can germinate over several months. Other weeds require relatively higher doses for complete control. In fields where reduced rates were applied or where an untimely rain reduced the amount of glyphosate entering weed leaf tissue, such species can survive and continue growing. Morning glory species are an example of a weed that often survives applications and can create problems later in the season.

Scientists at Iowa State University have done an excellent job tracking and explaining the factors giving rise to shifts in weed species in RR soybean fields. These factors include the time period over which weed seeds germinate and how susceptible a weed is to glyphosate. (For more information see http://www.weeds.iastate.edu/).[5]

1. Resistance

Some weeds have developed resistance to glyphosate (Horstmeier, 2001) and others are displaying rising tolerance (Hartzler, 1999). Glyphosate resistant horseweed, *Conyza Canadensis (L.) Cronq*., was discovered in 2000 in Delaware, following just three years of using glyphosate for weed control in predominantly no-till production systems (Herbicide Resistant Weeds website, http:www.weedresearch.com). Resistance levels between 8- and 13-fold were confirmed. In the last two seasons, comparable levels of resistance in horseweed have been found in several other states.

Since 1999, slipping efficacy in the control of waterhemp has been observed in a number of states, leading to considerable debate within the weed science community regarding whether observed waterhemp field failures have been caused by “greater tolerance” in certain waterhemp phenotypes, “reduced sensitivity,” or the emergence of resistance. Monsanto has a history of aggressively challenging claims from university weed scientists that resistance has emerged. In most Midwestern land grant universities, some weed science faculty members are either carrying out research with funding from Monsanto or are paid consultants supporting Monsanto efforts to promote adoption of Roundup Ready crops. When other scientists in these departments compile data that raises questions with the technology, evidence of waterhemp resistance for example, Monsanto soon learns of the results and typically challenges the findings and seeks to discourage their publication or presentation at public meetings.

Occasionally, Monsanto and other biotechnology companies go beyond challenging the results of individual research projects and make efforts to influence or control extramural research funding and policy outcomes. For example in 2001, a state legislature was considering passage of a bill imposing what was, in effect, a moratorium on the development of Roundup Ready wheat, in light of the lack of consumer acceptance for the technology. Monsanto publicly threatened that it would pull back all its agricultural research funding to the state’s land grant university if the bill passed. The threat worked; the legislature tabled the bill.

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[5] For more on resistance to herbicides, see the “International Survey of Herbicide Resistant Weeds” accessible at http://www.weedscience.org/in.asp; and several items on Ag BioTech InfoNet at http://www.biotech-info.net/herbicide-tolerance.html#soy).

2. Company Strategies in Response to Field Failures and the Risk of Resistance

Monsanto and other companies selling herbicide tolerant varieties have developed a strategy to deal with field failures, some of which are likely associated with weed shifts and/or the emergence of resistance. First, they acknowledge that weather conditions when glyphosate is applied are critical in determining efficacy -- rainfall soon after an application is likely to wash enough of the herbicide off weeds prior to translocation to render an application less than fully effective. Companies are quick to accept this as a plausible explanation of a field failure. Monsanto has included in its "Roundup TVP [Total Value Program] Rewards" package covering RR soybeans an allowance for one unexpected "annual weed flush" prior to canopy close, presumably the result of an application of Roundup followed soon thereafter by a rainfall event (Monsanto "2000 Technology Use Guide: Technical Information About Monsanto Technologies, Plaines Region").

Growers complying with all Monsanto TVP program requirements are eligible to receive at no added cost up to 24 ounces (1.5 pints) per acre of Roundup Ultra for an additional treatment. "Roundup TVP Rewards" requirements include purchasing Monsanto RR soybeans, signing the technology agreement, purchasing Monsanto brand herbicide, and making two or three applications of Roundup Ultra at a rate not less than 24 ounces per acre. A no-till grower exercising the "annual weed flush" option would be required to –

- Make a pre-plant burndown application of at least 24 ounces per acre;
- Apply at least two in-season applications, each at a minimum of 32 ounces per acre; and
- Make a fourth application to control the "annual weed flush."

Under this program, a minimum of 112 ounces (7 pints) of Roundup herbicide would be applied per acre, or 3.5 pounds of active ingredient per acre (3.9 kg/hectare). This volume of glyphosate herbicide use per hectare/acre is three-times the U.S. national average of herbicide use on soybeans and constitutes a dramatic increase in the selection pressure imposed on weed populations.

As a result of weed shifts and slipping efficacy of Roundup in the control of some weeds, most U.S. farmers growing RR soybeans now apply one to three active ingredients in addition to glyphosate. 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 for broadleaf weed management. Another product is typically applied to provide some residual grass control. Popular products include pendimethalin, imazethapry, and treflan. Table 11 displays a sample of 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 11. Changes in Cotton Insecticide Use by Family of Chemisty (million pounds a.i.)

	1964	1966	1971	1976	1982	1992	1998	2000
Organochlorines	54.6	45.4	33	18.6	1.2	1.2	0.3	0.5
Organophosphates	15.6	14.3	28.6	31.4	12.9	13.4	11.3	36.1
Carbamates	6.2	4.5	10.3	12.2	3.5	4	2.7	3.5
Pyrethroids	0	0	0	0	0.8	0.9	0.4	0.3
Other	1.6	0.7	1.5	2	1	0.3	0.1	0.1
Total Pounds Applied	78	64.9	73.4	64.2	19.4	19.8	14.8	40.5

* Totals may not add due to rounding.

Source: Calculated from USDA Chemical Use Surveys, multiple years.

The cost of this very-low dose program compares favorably to a Roundup-based program with RR varieties when the technology fee is counted as a cost of the herbicide program. Those farmers able to get through the season with two applications of Roundup will spend about $23.00 per acre with the technology fee ($16.77 for herbicide plus about $6.00 for the technology fee) and results in the application of 1.3 pounds of active ingredient per acre. 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 per acre.

B Evidence of Soybean Physiological and Disease Problems and Impacts on Yields

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 hectare/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 greater than 10 percent. Much work is underway to determine why.

1. 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 other factors. 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 hectare/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, eliminating 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 soybean varieties yielded 52 bushels per acre, placing the average magnitude of the RR yield drag relative to the best conventional varieties at 5.7 bushels per acre, or about 11 percent. In a direct comparison of RR varieties to their isolines, 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)

In 1998 a team of Kansas State University scientists assessed the impacts of applications of different herbicides on RR and conventional soybean variety yields and compared RR and conventional soybean yields (Hofer et al., 1999). Like the Nebraska study, no significant differences were found as a function of herbicides applied 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.

2. Physiological Growth Problems

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).

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). Soybean lignin production is one of several important physiological process controlled by phenylalanine, a key product of the shikimate pathway. This is the pathway impacted by the genetic transformation used to make soybeans tolerant of glyphosate.

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 in the next section, excessive heat is likely 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).

III. Possible Causes of Yield and Disease Problems in Roundup Ready Crops

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-enolpyruvoylshikimate-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 raised new concerns regarding the stability of gene expression (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, 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)

A. Changes in Soil Microbial Communities and Disease Pressure

A team of researchers at the University of Arkansas published an important paper in 2001, “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 on RR soybean growth and performance and on the efficiency of the soybean plant nitrogen fixation process. N-fixation in soybeans is, of course, a major agronomic advantage of soybeans and is critical in achieving optimal yields, while keeping fertilizer costs to a minimum.

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 in the United States 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 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 as influential.

The team sprayed Roundup on RR soybeans just as 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 lies in their finding in greenhouse experiments that glyphosate applications decrease RR soybean plant root growth (King et al., 2001). It is also well known that the N_2 fixation process in soybeans is 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.

A team of USDA Agricultural Research Service (ARS) scientists led by Krishna Reddy replicated the work by King et al. and found similar results (Reddy et al., 2000). This team also showed the potential for soybean plant injury at a 2.24 kg/hectare rate of application (2 pounds per acre) and alos noted greater potential for soybean injury at higher temperatures.

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 (SDS), a growing problem in several parts of the Midwest in recent years.

Four RR soybean varieties were tested at eight sites across Missouri. 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 conventional herbicides alone.

In the plots treated with just Roundup or with Roundup plus 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. Kremer believes that the buildup of Fusarium in soils planted to RR crops is caused by root exudates triggered when RR varieties are sprayed with glyphosate herbicide.

Root exudates from transgenic plants can trigger changes in soil microbial communities through a variety of mechanisms. Kremer suspects that something in the exudates are either directly benefiting certain Fusarium fungi, or alternatively, may be harming microorganisms that compete with Fusarium for resources and habitat in the rhizosphere. As a result, he has called for ecological assessment of the impacts of herbicide tolerant crops on rhizosphere microorganisms. Assessments should determine impacts on soil microbial community composition and interactions, as well as on plant defense responses to pathogens and other abiotic stresses, many of which are triggered or mediated by soil microorganism-root interactions.

Potential Impacts of Changes in Soil Microbial Communities

The buildup of Fusarium in Midwestern soils is a growing concern for several reasons. First, Fusarium species trigger a number of costly diseases in soybeans, corn and wheat, and any factor that leads to a buildup of Fusarium can, under some circumstances, heighten disease pressure and related yield losses.

Second, changes in the composition of soil microbial communities can increase the chances that nutrient cycling problems may become more common. There is evidence that glyphosate applications on RR crops can depress the levels of mycorrhizae in the rhizosphere, a critical issue given the role of mycorrhizae in making phosphorous bioavailable to plants.

Recent problems with swine reproductive efficiency points to a third potential problem. In 2001, a number of hog farmers reported psuedopregnancy problems in their herds (sows abort prior to delivery). They sought scientific help from USDA and university scientists, who traced the problem to elevated levels of certain Fusarium species in the corn being fed to the pigs. It has been known for years that certain Fusarium species can trigger swine psuedopregnancy, but the scientists were unable to explain why the levels had become high enough to trigger the problems experienced by this group of hog farmers. According to Dr. Robert Kremer, plant pathologists in the Midwest suspect that the buildup of Fusarium in the fields planted to RR soybeans for multiple years is one plausible explanation. It is not known what other factors must be in place for elevated levels of Fusarium in a field to lead to infections in corn grown in a subsequent season.

Despite the potential economic impact of this problem, Kremer reports that there are few scientists actively working on this problem because of a lack of public research support dedicated to exploring the potential impacts of herbicide tolerant varieties on soil microbial communities and plant disease status.

B. 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 questions to all farmers planting RR soybeans, since a variety of Fusarium species are almost always present 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.

Evidence suggests that impacts on plant defense mechanisms may be linked to altered patterns of gene expression in RR soybean plants following treatment with Roundup. Apparently, the EPSPS genetic transformation that makes plants able to withstand Roundup also impacts the plant's immune response. 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)

These scientists stressed the likely importance of this transformation by noting that up to 35 percent of soybean plant mass is represented by aromatic molecules derived from the shikimate pathway. Accordingly, the genetic transformation which makes RR soybeans able to tolerate glyphosate changes a pathway regarded as a sort of master control switch, if not the "nerve center," governing how plants respond to stress and pathogen attack.

As a result it is not surprising that such genetic transformation might, under some circumstances, lead to unanticipated and unintended consequences. Such impacts may arise from many combinations of conditions that can induce unusual protein-regulated stress and immune responses, directly or indirectly (Facchini et al., 2000). Indeed, the absence of such unintended effects in RR soybeans would be a surprising finding given the range of stress responses and DNA repair tools that RR soybean plants invoke in response to abiotic stress, pest feeding, or threats to genomic integrity.

1. 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. 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 reports its basic finding -- "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 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 for short periods in contrast to 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.

2. 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 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 in a recent review article –

> "...these efforts to alter plant metabolic pathways...have often produced unpredictable results, primarily due 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.

3. Possible Impacts of Gene Silencing

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 that are part of the plant's attempt to deal with drought, for example.

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.

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Appendix Table 1: Grams and Pounds of Glyphosate Active Ingredient at Various Rates of Application of Roundup Original and Ultra Herbicides

	Glyphosate in Grams	**Glyphosate in Pounds**
Container Volume		
One liter of Roundup	480	1.06
2.083 liters of Roundup	1,000	2.21
One gallon of Roundup	1,817	4
0.551 gallon of Roundup	1,000	2.21
Common Application Rates		
Glyphosate in pounds	453.59	1
Glyphosate in kilograms	1,000	2.205
One pint Roundup per acre	226.8	0.5
24 ounces Roundup (1.5 pints) per acre	340.2	0.75
32 ounces of Roundup (2 pints) per acre	453.6	1
2.5 liters per hectare	1,200	2.65
Source: Glyphosate in one liter and gallon of Roundup herbicide from the label for Roundup Original and Roundup Ultra herbicides.		
Liter of Roundup to gallons Roundup	0.264172	
Glyphosate in liter of Roundup to glyphosate in gallon of Roundup	0.264172	
Liter glyphosate in Roundup/hectare to pounds glyphosate/acre	0.4290	
Pounds glyphosate in Roundup/acre to kilograms glyphosate per acre	0.45359	
Pounds glyphosate in Roundup/acre to kilograms glyphosate per hectare	1.1208	
Kilograms glyphosate in Roundup/hectare to pounds glyphosate per hectare	2.2046	
Kilograms glyphosate in Roundup/hectare to pounds glyphosate per acre	0.8922	

Appendix Table 2: Conversion Factors for Comparing Pesticide Application Rates Between English and Metric Units of Measure

	Conversion Factor -- Multiply By	
Volume Conversions		
Liter of Roundup to gallons Roundup	0.264172	
Glyphosate in liter of Roundup to glyphosate in gallon of Roundup	0.264172	
Rate of Application Conversions		
Pounds glyphosate in Roundup/acre to kilograms glyphosate per acre	0.45359	
Pounds glyphosate in Roundup/acre to kilograms glyphosate per hectare	1.1208	
Kilograms glyphosate in Roundup/hectare to pounds glyphosate per hectare	2.205	
Kilograms glyphosate in Roundup/hectare to pounds glyphosate per acre	0.8924	
Other Conversion Factors		
Hectares to Acres	2.471	One hectare is 2.47 acres
Acres to hectares	0.40469	One acre is .405 of a hectare
Pound per Acre to Pound per Hectare	0.405	One pound per acre is .405 pounds per hectare
Liter per hectare to Liter per Acre	2.47	One liter per hectare is 2.47 liters per acre
Liter to pint	2.113	One liter is 2.11 pints
Pint to liter	0.473	One pint is .473 liters
Kg/hectare to pounds per acre	0.893	One kg/hectare is .893 of a pound per acre
Pounds per acre to kg/hectare	1.12	One pound/acre is 1.12 kg/hectare
Kilogram to pound	2.2046	One kilogram is 2.205 pounds
Pound to kilogram	0.45359	One pound is .454 of a kg
Pound to ounces	16	16 ounces in a pound
Pints to quarts	0.5	Two pints in a quart
Grams to ounces	0.03527	One gram is .03527 ounces
Ounces to grams	28.35	One ounce is 28.4 grams
Quarts in a gallon	0.25	Four quarts in a gallon
Liter to gallon	0.2641	One liter is .264 of 1 gallon
Gallon to liter	3.7864	One gallon is 3.786 liters

Appendix Table 4. Pounds Applied of Corn Herbicides in 1971, 1982 and 1991 - 2000 based on USDA Pesticide Use Data

	1971	1982	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
2,4,5-T	50,000											
2,4-D	9,144,000	5,135,801	2,800,000	2,832,000	3,586,000	3,631,000	3,770,000	3,237,000	2,087,000	3,475,000	2,536,000	2,359,000
acetamide										97,000	185,000	792,000
acetochlor						7,447,000	23,312,000	29,850,000	28,158,000	32,955,000	31,824,000	31,442,000
alachlor	8,360,000	52,242,968	37,174,000	40,129,000	32,078,000	21,325,000	8,718,000	10,188,000	4,576,000	4,898,000	4,573,000	4,748,000
ametryn		27,881	59,000	146,000			256,000			138,000	25,000	114,000
atrazine	52,000,000	69,647,409	52,060,000	54,939,000	49,553,000	45,412,000	45,735,000	53,466,000	47,155,000	53,507,000	54,780,000	53,954,000
bentazone		8,234	478,000	550,000	497,000	584,000	516,000	806,000	942,000	371,000	1,033,000	327,000
bromoxynil			1,344,000	1,389,000	1,364,000	1,446,000	1,251,000	1,345,000	1,031,000	916,000	844,000	884,000
butylate	5,818,000	54,887,203	8,478,000	8,117,000	5,441,000	2,117,000	1,795,000	2,475,000		406,000		
Carfentrazone-ethyl											32,000	54,000
chloramben		44,000	4,332									
clopyralid								29,000	134,000	354,000	607,000	640,000
cyanazine		20,553,073	23,161,000	26,691,000	26,453,000	27,689,000	23,335,000	20,795,000	16,490,000	9,479,000	3,378,000	865,000
dalapon	34,000	49,328										
diallate		3,424										
dicamba	284,000	2,108,500	3,556,000	5,068,000	4,598,000	6,322,000	5,762,000	5,545,000	5,797,000	3,692,000	2,029,000	3,132,000
Dicamba dimethylamine salt												394,000
dicamba dimethylammonium											1,446,000	
dicamba potassium salts										2,632,000	1,997,000	1,407,000
dichloroprop (2,4-DP)												10,000
Diflufenzopyr											578,000	157,000
dimethenamid						2,241,000	2,256,000	4,110,000	4,728,000	6,735,000	6,185,000	5,738,000
EPTC	292,000	8,334,277	14,355,000	10,594,000	11,098,000	6,124,000	7,102,000	5,117,000	3,173,000	5,894,000	1,470,000	2,884,000
flumetsulam						52,000	44,000	49,000	82,000	163,000	291,000	301,000
glufosinate ammonium										745,000	424,000	585,000
glyphosate		479,803	1,156,000	746,000	1,973,000	1,776,000	2,358,000	2,200,000	1,429,000	2,601,000	4,162,000	4,438,000
halosulfuron-methyl							20,000	46,000	34,000	32,000	75,000	
Halosulfuron												15,000
imazapyr										4,000	1,000	3,000
imazethapyr					11,000	37,000	26,000	20,000	12,000	22,000	32,000	22,000
Isoxaflutole											213,000	171,000

linuron	804,000	336,991	93,000	96,000			120,000			2,000		
MCPA	159,000											
mecoprop		3,187										
metolachlor		21,658,785	38,792,000	41,327,000	39,026,000	39,213,000	35,075,000	41,135,000	43,772,000	43,479,000	29,554,000	14,232,000
metribuzin					46,000	41,000	85,000	38,000	30,000	95,000	54,000	190,000
nicosulfuron			76,000	140,000	165,000	249,000	224,000	245,000	160,000	147,000	150,000	199,000
norea (noruron)	51,000											
paraquat dichloride		687,520	201,000	423,000	630,000	400,000	447,000	637,000	381,000	535,000	369,000	570,000
pendimethalin		296,056	2,745,000	3,091,000	2,825,000	1,806,000	2,628,000	2,631,000	1,764,000	1,611,000	776,000	2,360,000
petroleum oils	11,173,000											
primisulfuron-methyl			29,000	30,000	40,000	47,000	42,000	106,000	82,000	85,000	100,000	140,000
propachlor	21,300,000	3,492,825	1,456,000	1,506,000	1,260,000	1,184,000		337,000	347,000			
propazine	583,000											
prosulfuron								59,000	50,000	28,000	21,000	25,000
pyridate										140,000	2,150,000	2,268,000
rimsulfuron							4,000	6,000	11,000	9,000	74,000	82,000
sethoxydim										9,000		
simazine	920,000	3,252,542	1,081,000	1,147,000	1,118,000	972,000	1,977,000	2,059,000	979,000	915,000	1,555,000	2,029,000
S-Metolachlor												15,383,000
Sulfosate											77,000	173,000
thifensulfuron										3,000	123	6,000
thifensulfuron-methyl							2,000	3,000	6,000			
tridiphane			264,000	123,000		66,000						
trifluralin	29,000	52,654	111,000		114,000						41,000	43,000
vernolate		146,526										
All Herbicides Applied	111,001,000	243,448,986	189,473,332	199,084,000	181,876,000	170,181,000	166,860,000	186,534,000	163,410,000	176,174,000	153,641,123	153,136,000
Average Pounds per Planted Acre	1.50	2.97	2.49	2.79	2.77	2.72	2.60	2.66	2.63	2.47	2.25	2.08
Acres Planted	74,179,000	81857000	75951000	71,375,000	65,690,000	62,500,000	64,105,000	70,250,000	62,200,000	71,400,000	68,300,000	73,800,000

Appendix Table 4. Pounds Applied of Corn Herbicides in 1971, 1982 and 1991 - 2000 based on USDA Pesticide Use Data

	1971	1982	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
2,4,5-T	50,000											
2,4-D	9,144,000	5,135,801	2,800,000	2,832,000	3,586,000	3,631,000	3,770,000	3,237,000	2,087,000	3,475,000	2,536,000	2,359,000
acetamide										97,000	185,000	792,000
acetochlor						7,447,000	23,312,000	29,850,000	28,158,000	32,955,000	31,824,000	31,442,000
alachlor	8,360,000	52,242,968	37,174,000	40,129,000	32,078,000	21,325,000	8,718,000	10,188,000	4,576,000	4,898,000	4,573,000	4,748,000
ametryn		27,881	59,000	146,000			256,000			138,000	25,000	114,000
atrazine	52,000,000	69,647,409	52,060,000	54,939,000	49,553,000	45,412,000	45,735,000	53,466,000	47,155,000	53,507,000	54,780,000	53,954,000
bentazone		8,234	478,000	550,000	497,000	584,000	516,000	806,000	942,000	371,000	1,033,000	327,000
bromoxynil			1,344,000	1,389,000	1,364,000	1,446,000	1,251,000	1,345,000	1,031,000	916,000	844,000	884,000
butylate	5,818,000	54,887,203	8,478,000	8,117,000	5,441,000	2,117,000	1,795,000	2,475,000		406,000		
Carfentrazone-ethyl											32,000	54,000
chloramben		44,000	4,332									
clopyralid								29,000	134,000	354,000	607,000	640,000
cyanazine		20,553,073	23,161,000	26,691,000	26,453,000	27,689,000	23,335,000	20,795,000	16,490,000	9,479,000	3,378,000	865,000
dalapon	34,000	49,328										
diallate		3,424										
dicamba	284,000	2,108,500	3,556,000	5,068,000	4,598,000	6,322,000	5,762,000	5,545,000	5,797,000	3,692,000	2,029,000	3,132,000
Dicamba dimethylamine salt												394,000
dicamba dimethylammonium											1,446,000	
dicamba potassium salts										2,632,000	1,997,000	1,407,000
dichloroprop (2,4-DP)												10,000
Diflufenzopyr											578,000	157,000
dimethenamid						2,241,000	2,256,000	4,110,000	4,728,000	6,735,000	6,185,000	5,738,000
EPTC	292,000	8,334,277	14,355,000	10,594,000	11,098,000	6,124,000	7,102,000	5,117,000	3,173,000	5,894,000	1,470,000	2,884,000
flumetsulam						52,000	44,000	49,000	82,000	163,000	291,000	301,000
glufosinate ammonium										745,000	424,000	585,000
glyphosate		479,803	1,156,000	746,000	1,973,000	1,776,000	2,358,000	2,200,000	1,429,000	2,601,000	4,162,000	4,438,000
halosulfuron-methyl							20,000	46,000	34,000	32,000	75,000	
Halosulfuron												15,000
imazapyr										4,000	1,000	3,000
imazethapyr					11,000	37,000	26,000	20,000	12,000	22,000	32,000	22,000
Isoxaflutole											213,000	171,000
linuron	804,000	336,991	93,000	96,000			120,000			2,000		
MCPA	159,000											
mecoprop		3,187										
metolachlor		21,658,785	38,792,000	41,327,000	39,026,000	39,213,000	35,075,000	41,135,000	43,772,000	43,479,000	29,554,000	14,232,000
metribuzin					46,000	41,000	85,000	38,000	30,000	95,000	54,000	190,000
nicosulfuron			76,000	140,000	165,000	249,000	224,000	245,000	160,000	147,000	150,000	199,000
norea (noruron)	51,000											
paraquat dichloride		687,520	201,000	423,000	630,000	400,000	447,000	637,000	381,000	535,000	369,000	570,000
pendimethalin		296,056	2,745,000	3,091,000	2,825,000	1,806,000	2,628,000	2,631,000	1,764,000	1,611,000	776,000	2,360,000
petroleum oils	11,173,000											
primisulfuron-methyl			29,000	30,000	40,000	47,000	42,000	106,000	82,000	85,000	100,000	140,000
propachlor	21,300,000	3,492,825	1,456,000	1,506,000	1,260,000	1,184,000		337,000	347,000			
propazine	583,000											
prosulfuron								59,000	50,000	28,000	21,000	25,000
pyridate										140,000	2,150,000	2,268,000
rimsulfuron							4,000	6,000	11,000	9,000	74,000	82,000
sethoxydim										9,000		
simazine	920,000	3,252,542	1,081,000	1,147,000	1,118,000	972,000	1,977,000	2,059,000	979,000	915,000	1,555,000	2,029,000
S-Metolachlor												15,383,000
Sulfosate											77,000	173,000
thifensulfuron										3,000	123	6,000
thifensulfuron-methyl							2,000	3,000	6,000			
tridiphane			264,000	123,000		66,000						
trifluralin	29,000	52,654	111,000		114,000						41,000	43,000
vernolate		146,526										
All Herbicides Applied	111,001,000	243,448,986	189,473,332	199,084,000	181,876,000	170,181,000	166,860,000	186,534,000	163,410,000	176,174,000	153,641,123	153,136,000
Average Pounds per Planted Acre	1.50	2.97	2.49	2.79	2.77	2.72	2.60	2.66	2.63	2.47	2.25	2.08
Acres Planted	74,179,000	81857000	75951000	71,375,000	65,690,000	62,500,000	64,105,000	70,250,000	62,200,000	71,400,000	68,300,000	73,800,000