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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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Executive Summary

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. The consolidation of information is conducted 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. The paper first looks at rates of adoption, herbicide use rates and yield data.

As well, the paper examines 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 the effects of current practice also have some worrying implications. Poor management of the new technologies risks undermining their effectiveness, while selection pressures lead to weed and pest shifts as well as increased resistance. The study predicts that in Argentina, with current levels and patterns of use, these problems should be surfacing soon, and may already exist.

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. There are also 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.

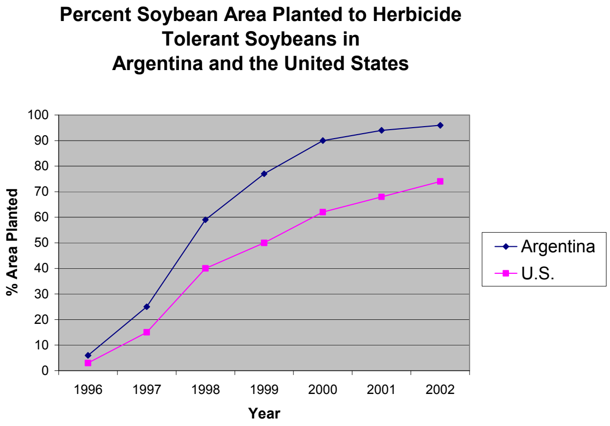
Rates of Adoption, Herbicide Use Rates and Yield Data

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 per cent hectares/acres planted to herbicide-tolerant soybean varieties rose rapidly to about 90 per cent in Argentina in 2000 and over 95 per cent in 2002, but grew more slowly from 1998 to 2002 in the United States, reaching around 75 per cent 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: U.S. and Argentina



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 year[1] are estimated, as well as total use in kilograms and pounds and litres 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 percentage of Argentina soybeans planted using the no-till system. Essentially all no-till cropland is treated with a burndown application of glyphosate herbicide right before, or at, planting, as well as one or two applications during the season. In Argentina,

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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.

about one-half of 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 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 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 5–10 per cent 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 six per cent 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 the 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.

Table 1: Extent of Adoption, Rates of Application and Use of Glyphosate (Litres 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	Percentage Hectares/ Acres Planted to RR Soybeans	Hectares Planted to RR Soybeans	Acres Planted to RR Soybeans	Glyphosate Active Ingredient							Litres 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 per cent Argentina soybean acreage is planted using no-tillage systems and 30 per cent using conventional/conservation tillage. "Per cent Hectares Planted to RR Soybeans" values are consistent with the Qaim and Traxler estimate that 90 per cent 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. Per cent U.S. acres planted to RR soybeans based on 62 per cent of soybean acres treated with glyphosate herbicides in 2000 (USDA National Agricultural Statistics Service [NASS], 2001), assuming that six per cent 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 per cent of soybean acres were planted under conventional/conservation tillage and 28 per cent under no-till (see Table 1.1 in *Troubled Times* (Benbrook, 2001).

3. Glyphosate sales in Argentina is 82.35 million litres of formulated commercial product with 480 grams per litre of glyphosate active ingredient, of which about 65 per cent is for soybeans (53.5 million litres) (Qaim and Traxler, 2002). Average crop year rate of application on soybeans is (53.5 million litres divided by 9.288 million hectares planted, or 5.76 litres 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.

Yield data

There is clear and consistent evidence in the U.S. that since introduction in 1996 most RR soybean cultivars produce 5–10 per cent 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 six per cent. 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 per cent 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 one per cent. In Iowa trials, the RR yield drag was just under 19 per cent across 17 companies.

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. 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 less than 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. And since the introduction of RR soybeans in the U.S., total acres planted using no-till has increased only minimally, from 30.5 per cent in 1996 to 33.9 per cent 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.

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 led 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 one 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.

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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*.

[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.

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.

Emerging Issues Impacting the Performance of RR Soybean Cultivars

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; and
- potential food safety hazards.

Impacts on soil microbial communities and 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 build-up of Fusarium in fields following one or more years of RR soybean production. RR 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 build-up 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 per cent 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.

Plant Physiology and 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.

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.

References and Further Information

Internet Sources of Varietal Trial Data

Illinois: Varietal Information Program for Soybeans (access for all years)
http://web.aces.uiuc.edu/VIPS/v2home/VIPS2Home.cfm
2000 data: http://www.cropsci.uiuc.edu/vt/soybean.html

Minnesota: Soybean Variety Trials Resource Pages
http://www.maes.umn.edu/maespubs/vartrial/cropages/soypage.html
1999-2000 data (190K pdf file)
http://www.maes.umn.edu/maespubs/vartrial/pdfpubs/2001soy.pdf

Nebraska: Main page
http://varietytest.unl.edu/soytst/2000/
Soybean booklet in pdf (1254K)
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