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Review

Economic impacts of glyphosate-resistant crops

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Abstract: Glyphosate-resistant crops have been widely planted since their introduction in 1996. Growers have numerous choices for herbicide treatments and have chosen to plant glyphosate-resistant crops on the basis of economic factors. The economic effects of the widespread planting of glyphosate-resistant crops have included reductions in herbicide expenses, increases in seed costs, increased yield and changes in the relative profitability of crops that has resulted in changes in which crops are planted. In addition, non-pecuniary benefits have accrued as a result of the simplicity of weed management in the glyphosate-resistant crop systems.

Keywords: herbicides; glyphosate; economic benefits; biotechnology; soybean; maize; canola; cotton

1 INTRODUCTION

Since their introduction in 1996, genetically engineered herbicide-resistant crops (HRCs) have been planted on an increasing number of hectares each year, and totaled 83 million ha worldwide in 2006.[1] HRC-planted areas as a percentage of total worldwide areas in 2006 were: soybeans 64%, maize 9%, canola 18% and cotton 16%.[1] The USA is the leading country in terms of HRC area, with 42 million ha of HRCs of maize, cotton, soybeans and canola.[2] Glyphosate-resistant crops in the USA account for 100% of the hectares of HR soybeans, 89% of the hectares of HR maize, 98% of the hectares of HR cotton and 62% of the hectares of HR canola.[3] Glufosinate-resistant hectares account for the remaining HR hectares. Along with the increase in glyphosate-resistant crop (GRC) hectares, there has been a significant increase in the amount of glyphosate usage which grew from 1.8 million kg on US maize, soybeans and cotton hectares in 1990 to 45 million kg in 2005[4] (Fig. 1).

Glyphosate came off-patent in the USA in 2000, and a significant number of generic glyphosate products have been introduced. The price of glyphosate for US farmers declined by about 40% between 1999 and 2005[5] (Fig. 2). Also declining in price were many other herbicides in the USA, with declines in price of 20–40% common in the 1999–2005 period.[5] Growers have numerous choices for herbicide treatments. Glyphosate usage with GRCs has reduced the use of many herbicides that were used previously.

2 USA – SOYBEANS

The percentage of soybean hectares in the USA planted with GRCs grew from 13% in 1997 to 88% in 2005.[3] One hundred per cent of the US hectares of HR soybeans consist of GR soybeans (Roundup Ready). Glyphosate-resistant soybeans were rapidly adopted, in spite of early studies showing no significant advantage in net returns or yield over conventional systems.[6] The largest undertaking to analyze farmer experiences with herbicide-resistant soybeans was a special USDA survey of growers in 17 states conducted in 1997 and 1998. This survey showed that the increases in soybean yields associated with adoption of HRCs were statistically significant but small.[7] No significant association with net farm income was evident in 1997 or 1998. A 2000 survey in Delaware (a state not included in the 1997/98 USDA surveys) showed that farmers planting HRC soybeans achieved a yield of 7.4 bushels ha^{-1} more than a farmer not using the technology and saved approximately \$12 ha^{-1} in weed control costs.[8] Soybean production data for Pennsylvania in 1999 were analyzed, and the conclusion was that farmers who adopted HRC soybeans were more technically efficient in their use of resources than non-adopters.[9] Economists concluded that the widespread adoption of HRC soybeans clearly resulted in production costs being significantly lower, making GRC soybeans profitable for the vast majority of growing conditions and farm types throughout the USA.[10]

The early USDA research led to the hypothesis that adoption was driven by 'unquantified' advantages such as simplicity and flexibility, which translate into reduced managerial intensity, freeing time for other uses.[6] Herbicide-resistant soybeans save managerial time by allowing farmers to apply one herbicide product over the soybean crop at any stage of growth, instead of using several herbicides to control a wide range of weed species. Other advantages of the GRC system are less concern with efficacy on the basis of

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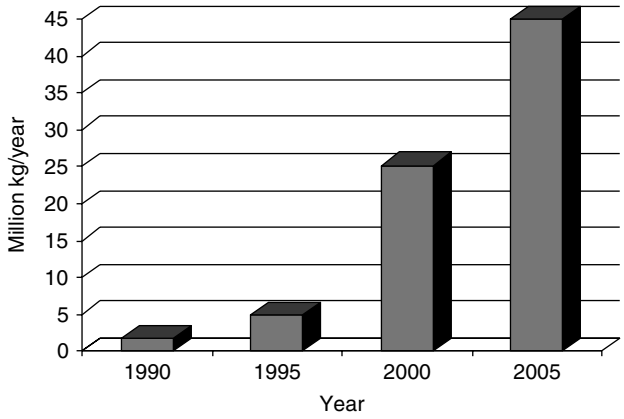

Figure 1. Glyphosate use: soybean/maize/cotton – USA.

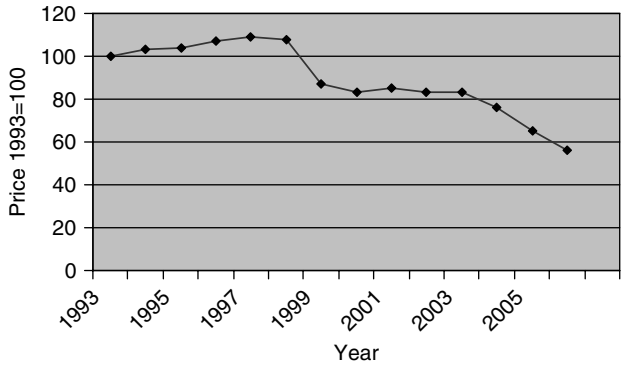

Figure 2. Glyphosate price in the USA.

weed height, less concern of injury to the soybean crop on the basis of plant height and less concern of injury to rotational crops. In the mid-1990s (before the introduction of GRCs), 23% of US soybean hectares were treated with four or more active ingredients, while 28% were treated with three active ingredients.[11] These combinations were no longer necessary with GRCs because of the broad-spectrum control efficacy of glyphosate.

An analysis of data from a 2000 USDA survey indicated that the adoption of GRC soybeans reduces household labor by 23%.[12] Assuming that a farmer has an average-sized soybean farm (209 ha) and uses the average amount of labor per hectare (3.1 h) suggests that adoption of the GRC system reduces the quantity of household labor by a total of 149 h or about 15 ten-hour days throughout the growing season.[12] By substituting GRC soybeans for household labor, farmers are freeing up time for other activities including leisure and off-farm employment.

Off-farm income received by farm operators and their spouses has grown dramatically over recent decades. The off-farm income share of total household income of US farmers has risen from about 50% in 1960 to more than 80% over the past 10 years.[6] Higher off-farm income is significantly related to the adoption of technologies that economize on management time. USDA research demonstrated that a 16% increase in off-farm household income is associated with a 10% increase in the probability of adopting herbicide-resistant soybeans.[6,13] On the other hand, adoption of herbicide-resistant soybeans did not have a significant relationship with household income from farming.[6] A recent study relied on a 2002 survey of US soybean farmers to estimate the non-pecuniary characteristics of the adoption of GRC soybeans.[14] The study concluded that the non-pecuniary value of the GR soybeans was \$12 ha^{-1}, with convenience making up 50% of the value, while operator, worker and environmental safety accounted for the remaining value.

The widespread planting of GR soybeans with the associated use of glyphosate has resulted in significant changes in herbicide use patterns and costs for US soybean growers. The use of tank mixtures and sequential applications of more than one herbicide has declined as many growers have elected to rely exclusively on glyphosate for weed control in soybean.[15] The number of active ingredients used on at least 5% of the nation's soybean hectares has declined from 19 in 1996 to only one (glyphosate) in 2005[4] (Fig. 3). The US market for soybean herbicides declined by \$1 billion between 1996 and 2004.[16] (Fig. 4).

On the other hand, USDA cost of production budgets show that the reduction in the cost of herbicides has been balanced out by an increase in the cost of seed for US soybean growers.[17] Between 1996 and 2005, the cost of herbicides for US soybean growers declined by \$27 ha^{-1}, while seed costs rose by \$32 ha^{-1} [16] (Fig. 5).

The National Center for Food and Agricultural Policy (NCFAP) has issued four reports estimating the value that farmers receive by planting GR

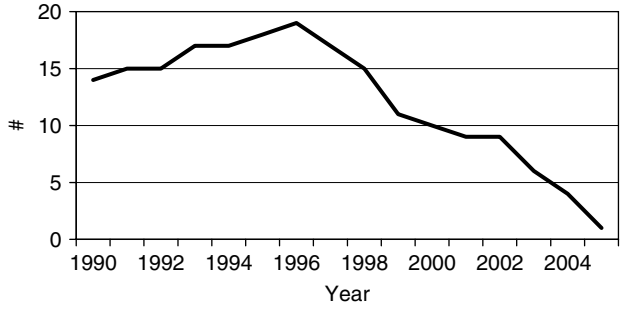

Figure 3. Number of herbicide active ingredients applied on ≥5% of US soybean hectares.

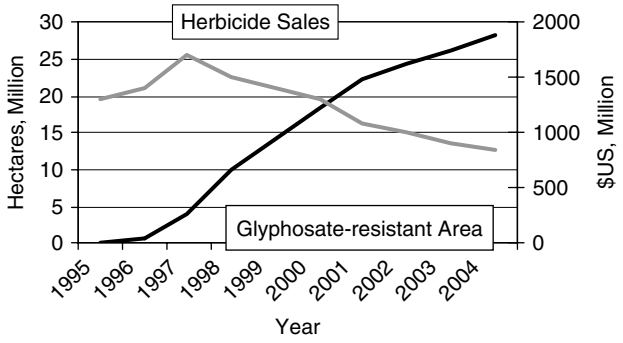

Figure 4. Performance of the US soybean market.

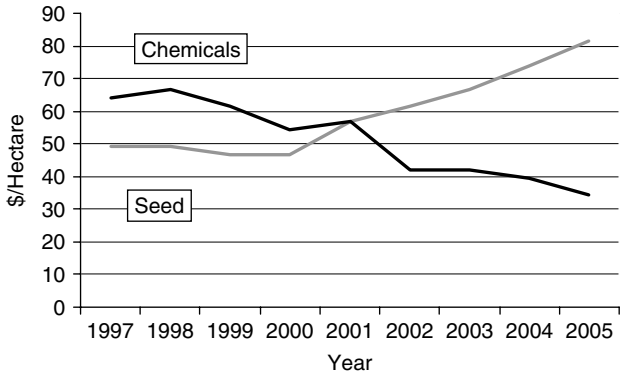

Figure 5. US soybean production costs.

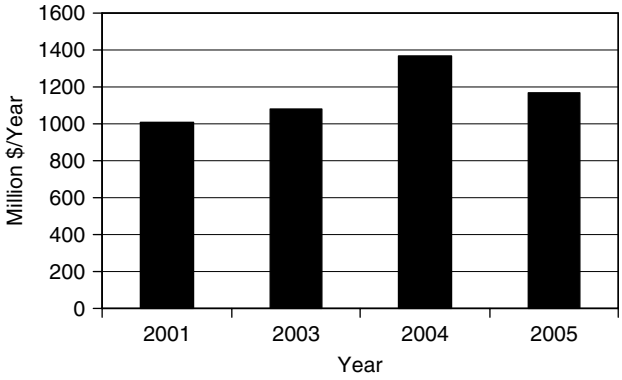

Figure 7. Glyphosate-resistant soybeans: net grower value.

soybeans.[3,18–20] The NCFAP studies are based on a simulation of the herbicide treatment program that could be used by state to substitute for the glyphosate program, with control of all the key weed species. The majority of the alternative programs consist of a pre-emergence application (using 1–2 herbicides) followed by a post-emergence application (with 1–2 herbicides) in comparison with 1–2 glyphosate applications in the GR crop. The cost of the alternative program is compared with the cost of the glyphosate program. In 2005 the glyphosate program was estimated to cost less than the effective alternative programs by an average of \$44.67 ha^{-1} for an aggregate value of \$1.17 billion on the nation's 26.2 million glyphosate-resistant hectares. The NCFAP study for 2005 notes that, because of an increase in the premium fees for the glyphosate-resistant seed in 2005 to \$25 ha^{-1} in comparison with a \$20 ha^{-1} premium fee in 2004, the aggregate net value of the glyphosate program was reduced by \$200 million. The per-hectare premium for glyphosate-resistant seed was estimated at \$15 in 2001 and \$17 in 2003 in the NCFAP reports (Figs 6 and 7). Relying largely on the NCFAP studies, a recent report estimates the cumulative farm income benefits of planting GR soybeans in the USA at \$6.4 billion for 1996–2004.[21]

The glyphosate-resistant weed control program has reduced the presence of foreign matter in soybean shipments to grain elevators.[22] Before using the glyphosate-resistant soybean system, because of weeds such as sicklepod, late-emerging grasses and cocklebur, the foreign matter content of many shipments in southeastern states ranged from 5 to 25%. Since using glyphosate-resistant soybeans, the foreign matter in most soybean shipments has fallen to 1–2%.

The glyphosate-resistant weed control package for soybeans has led to changes in rotation and fallowing practices. In Louisiana, conventional practice for many years has been to grow sugarcane for 3–5 years, followed by crop destruction and a fallow period when glyphosate is used to reduce rhizome Johnson grass levels.[23] Research has shown that, instead of fallowing, the field can be planted with glyphosate-resistant soybeans and the glyphosate usage will reduce the Johnson grass levels for the subsequent sugarcane crop while at the same time resulting in a profitable soybean crop harvest instead of a non-crop fallow period.

In North Dakota and Minnesota the introduction of glyphosate-resistant soybeans has led to increased planting of soybeans owing to the ease of weed control and favorable economics.[24] This trend to soybeans has transpired mostly at the expense of wheat – a crop for which glyphosate-resistant varieties are not available. Between 1995 and 2005, North Dakota farmers increased soybean plantings by 810 000 ha while reducing wheat hectares by an equivalent number.[25]

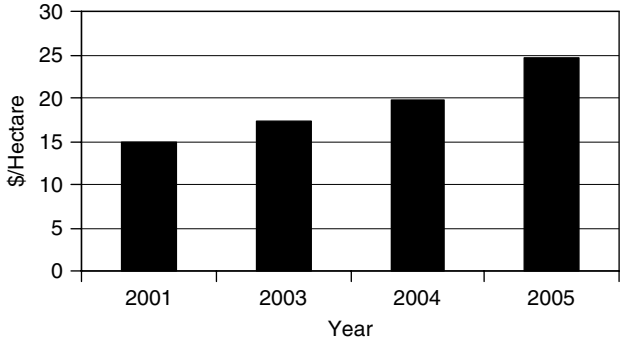

Figure 6. Glyphosate-resistant soybean seed premium.

3 USA – MAIZE

Thirty-five per cent of US maize hectares were planted with HR seed in 2005, which represented a significant increase from 21% in 2004 and 8% in 2001. Reasons for this increase in adoption include increased availability of the trait in hybrids suited to various geographic locations and the resolution of trade restrictions in export markets. Eighty-nine per cent of the US hectarage of HR maize is glyphosate resistant, while the remainder is glufosinate resistant.

Weed control strategies in HRC maize, unlike soybeans, necessitate the use of pre-emergence residual herbicides in addition to post-emergence applications of glyphosate or glufosinate.[3] Residual

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herbicides are needed in maize owing to its earlier time of planting and its greater susceptibility to early-season weed competition compared with soybean. As a result, pre-emergence residual herbicides (at half-rates) have become the basis of weed management programs in HRC maize.[3]

There were no major changes between 2001 and 2006 in the prices of herbicides traditionally used on US maize production (atrazine, dicamba and acetochlor).[5] The number of active ingredients applied to >10% of US maize hectarage stayed the same (six) in 2005 as it was in 2000.[4] Glyphosate, mesotrione and S-metolachlor replaced dicamba, flumetsulam and metolachlor in the 10% category of use. Atrazine continued to be used on approximately two-thirds of US maize hectarage throughout the period 2000–2005.

The NCFAP study estimates that the cost advantage to the HR maize weed control program in 2005 was \$23.73 ha^{-1} in comparison with effective weed control programs in conventional maize. With 11.3 million ha of HR maize planted in 2005, the aggregate net value of HR maize was estimated at \$269 million. The premium for glyphosate-resistant seed was estimated at \$17 ha^{-1} in 2005 in comparison with \$15 ha^{-1} in 2001–2004. Relying largely on the NCFAP studies, a recent report estimates the cumulative farm income benefits of planting HR maize in the USA at \$564 million for 1996–2004.[21]

4 USA – COTTON

Glyphosate-resistant cotton hectares increased from 4% of US hectarage in 1997 to 80% in 2005[3] (Fig. 8). The benefits of a glyphosate-resistant cotton weed control system include broad-spectrum weed control, convenience, simplicity, increased rotational options, increased efficacy and crop safety and reduced labor.[26] Changes in the production system since the development of glyphosate-resistant technology include less tillage, more narrow-row cotton, more hectares per grower, larger spray booms, fewer herbicide modes of action used during the growing season, reduced use of soil-applied herbicides at planting and reduced labor and machinery requirements.[26] In many regions, tillage, spot treatments, early post-emergence-directed applications and hand hoeing have decreased because of this technology.[27] The number of herbicide active ingredients used on 10% of US cotton hectares declined from 10 in 1997 to 4 in 2005.[4] A 2004 survey of Mississippi cotton farmers indicated their marginal willingness to pay for herbicide-resistant variety relative to the conventional variety as \$163 ha^{-1}.[28]

The NCFAP study estimated that the cost advantage of the herbicide-resistant cotton weed control program was \$264 million in 2004.[3] In the 2005 crop season, there was a significant increase in the seed premium cost for glyphosate-resistant cotton which doubled from the 2004 amount of \$35 ha^{-1} to \$69 ha^{-1}[13] (Fig. 9). As a result, the net value of the herbicide-resistant system was reduced to \$39 million in 2005[3] (Fig. 10).

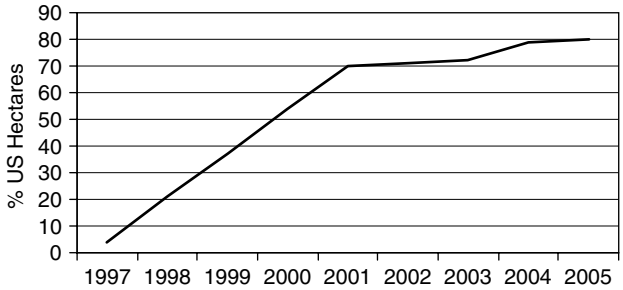

Figure 8. Glyphosate-resistant cotton adoption.

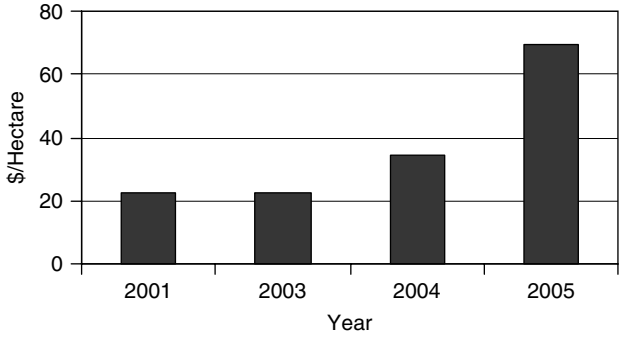

Figure 9. Glyphosate-resistant cotton seed premium.

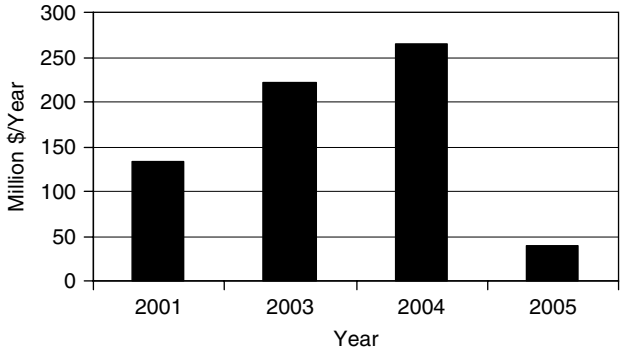

Figure 10. Glyphosate-resistant cotton: net grower value.

Relying largely on the NCFAP studies, a recent report estimates the cumulative farm income benefits of planting HR cotton in the USA at \$746 million for 1996–2004.[21]

5 USA, CANADA – CANOLA

Ninety-three per cent of US canola hectarage was planted with genetically engineered herbicide-resistant varieties in 2005.[3] Of the total national hectarage, glyphosate-resistant canola was planted on 62% of the hectares, whereas glufosinate-resistant canola was planted on 31% of the hectares.[3] The steady increase in the market share of glufosinate-resistant canola has been a trend since 2002 and is attributed to the availability of the trait in high-yielding varieties and also to a greater choice of varieties.[3] Glufosinate generally provides acceptable weed control in canola

regions. Both glufosinate and glyphosate provide viable weed management options to canola growers owing to their broad spectrum of activity and economic control of problem weeds such as kochia, Canada thistle, wild buckwheat, wild oat and yellow foxtail and seed contaminants such as wild mustard that may cause price discounts or rejection in the market.[3]

The NCFAP study estimates that alternative herbicide programs with conventional canola would cost US canola growers about \$96 ha^{-1}, while the glyphosate-resistant and glufosinate-resistant programs cost \$59 and \$69 ha^{-1} respectively.[3] Overall, NCFAP estimates that US canola growers accrued \$14.4 million in net value by planting the herbicide-resistant varieties in 2005.[3] Relying largely on the NCFAP studies, a recent report estimates the cumulative farm income benefits of planting HR canola in the USA at \$96 million for 1996–2004.[21] Included in this estimate is a yield effect of +6% for the herbicide-resistant canola.

In Canada, the area of glyphosate-resistant canola cultivars increased from about 26% in 1997 to 93% in 2004.[29] Cultivars that are glyphosate-resistant gained popularity in Canada owing to increased flexibility in timing of weed control, lower herbicide costs, fewer restrictions on the range of weed and crop growth stages for herbicide application and reduced crop injury caused by herbicide mixtures.[29] Growers have reported that their rotations are more flexible, and that they are able to seed earlier in the spring or fall, thus benefiting from soil moisture conservation.[30] In addition, there have been reports that growing glyphosate-resistant canola cultivars can result in higher economic returns than in the case of more traditional herbicide systems.[30] A 2000 survey of Canadian canola growers indicated that the glyphosate-resistant system resulted in an approximate minimum \$15 ha^{-1} profit advantage over conventional systems.[30] The herbicide-resistant system was estimated to result in a 10% yield advantage over conventional systems, thus contributing to an overall increase in canola production.[30] Studies in Canadian canola showed that glyphosate applied once or twice in-crop provided lower dockage (7–8% vs 10–15%) and higher canola yield (1700 kg ha^{-1} vs 1500–1600 kg ha^{-1}) than alternatives applied in the fall or in-crop.[31] The in-crop glyphosate applications resulted in higher net revenues than any of the other treatments (\$CAN 320–350 ha^{-1} vs \$CAN 165–286 ha^{-1}).[31] A recent article estimated that the contribution of HR canola varieties to increased yields of the crop in Canada is about 6.8% at the national level.[32] Relying largely on these impact studies, a recent report estimated the cumulative farm income benefits of planting HR canola in Canada at \$617 million for 1996–2004.[21] Included in this estimate is a yield effect of +10.7% for the herbicide-resistant system.

6 OTHER COUNTRIES

Glyphosate-resistant soybeans were released in Argentina in 1996 and were rapidly adopted by farmers, reaching a share of over 90% of the national soybean hectares in 2001.[33] In contrast to intellectual property protection in the USA, glyphosate-resistant technology is not patented in Argentina. Argentine farmers pay a relatively small price mark-up when they buy glyphosate-resistant soybeans, and, under national law, they are allowed to use farm-saved seeds.[33] An analysis of farm-level effects in Argentina was carried out on the basis of a survey of soybean farmers in 2001.[33] Farmers reported significant reductions in expenditures for herbicides in the glyphosate-resistant system. They also reported a reduced time needed for harvesting. Owing to the reduced incidence of green weeds in glyphosate-resistant fields, the combine harvester can be operated at higher speed without the danger of clogging. Eighty-five per cent of the Argentine soybean farmers stated greater flexibility and ease of management among the most important advantages of glyphosate-resistant soybeans. Glyphosate-resistant soybeans caused a sizable expansion of the overall soybean area in Argentina from 5.9 million ha in 1996 to 14.0 million ha in 2004. In part, soybean replaced other crops that became comparatively less profitable. New lands, which were not cultivated previously, were taken into glyphosate-resistant soybean production. In particular, these were pastures and bush lands on which cultivation had been difficult in the past owing to heavy weed infestation.[33]

For Argentina in 2004 it was estimated that the cost saving for glyphosate-resistant soybeans was \$30 ha^{-1} based on a cost of the technology of \$3 ha^{-1} for a net saving of \$27 ha^{-1}.[21] In aggregate, the net increase in farm income at the national level was estimated at \$415 million in 2004.[21] It has been estimated that an additional economic impact was the effect of glyphosate-resistant soybeans on the scale of growers planting a second crop of soybeans in the same growing season. The second crop is facilitated substantially by the ease of management of the glyphosate-resistant soybean crop, which allows farmers to use reduced or no-till systems and hence allows additional time for planting, growing and harvesting a second crop.[21] The increase in Argentine farm income from facilitating additional second cropping was estimated at \$1.7 billion in 2004.[21] Overall, Argentine growers gained \$9.96 billion in cumulative farm income benefits in 1996–2004 owing to the planting of glyphosate-resistant soybeans.[21] Aggregate net farm income benefits in 1996–2004 from planting glyphosate-resistant soybeans are estimated for Brazil at \$829 million, for Paraguay at \$80 million and for Canada at \$55 million.[21]

Glyphosate-resistant soybeans have been grown commercially in Romania since 1999 and were planted on 55–60% of the hectares in 2003.[34] The average impact on soybean yields is estimated to have been +31% owing to improved weed control, especially

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of difficult-to-control established weeds like Johnson grass.[34] Most farmers have also benefited from a 2–3% improvement in the price received for their soybeans, arising from improved harvest quality due to less weed contamination. The adoption of glyphosate-resistant soybeans in Romania has increased the value of Romanian soybeans by 14–19%.[34] Glyphosate-resistant soybean has become the most profitable arable crop grown in Romania.

7 CONCLUSION

The farmer's decision to use glyphosate with GRC varieties is based on economic factors. The widespread planting of GRCs has led to significant economic impacts that have been measured at the farmer level and for the agrochemical industry as a whole. Growers are estimated to be saving over $1 billion in herbicide costs as a result of the planting of HRCs. This cost saving for farmers has resulted in a corresponding decline in the sales of herbicides by agrochemical companies in the USA. On the other hand, the decrease in herbicide sales has been made up for in increased cost of seeds owing to premiums paid for GR seed.

The value of planting HR crops has been estimated primarily by simulating the costs of alternative weed control programs that could deliver the same weed control benefits as the GRC program. These alternative programs cost more than the GRC system, resulting in a net value gain for farmers who use the GRC system. In addition, aggregate yield increases are calculated for canola in Canada and the USA. The value of a second crop of soybeans in Argentina has been estimated and attributed to GR soybeans.

Worldwide cumulative farm income benefits from planting herbicide-resistant crops in 1996–2004 have been estimated at $19 339 million, with soybeans accounting for $17 300 million, maize accounting for $580 million, cotton accounting for $746 million and canola accounting for $713 million.[21] These farm income benefits were distributed by country as follows: Argentina $9965 million, USA $7777 million, Brazil $829 million, Canada $688 million and Paraguay $80 million.[21] A significant increase in the GR crop seed premium in the USA has lowered the aggregate net value to US cotton growers.

Much recent research has focused on the non-pecuniary value of GR crops that involve less management time. In the USA, the non-pecuniary value of GR soybeans has been estimated at $12 ha^{-1}. Reductions in herbicide expenditures have occurred as a result of widespread adoption of GR crops. However, the costs of seeds have increased as a result of premiums for GR seeds. For soybeans in the USA, the increase in seed costs balance out the decrease in herbicide costs. Between 2001 and 2005, aggregate US herbicide purchases declined by $300 million, which was almost exactly balanced by an increase of $312 million in the premiums for herbicide-resistant crop seeds.[35]

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REFERENCES

1 James C, *Global Status of Commercialized Biotech/GM Crops: 2006.* International Service for the Acquisition of Agri-Biotech Applications, Brief No. 35 (2006).
2 USDA, *Acreage*. National Agricultural Statistics Service (2005).
3 Sankula S, *Quantification of the Impacts on U.S. Agriculture of Biotechnology-Derived Crops Planted in 2005*. National Center for Food and Agricultural Policy (2006).
4 USDA, *Agricultural Chemical Usage, 2005 Field Crops Summary*. National Agricultural Statistics Service (2006).
5 USDA, *Agricultural Prices*. National Agricultural Statistics Service (2006).
6 Fernandez-Maizeejo J, *Off-Farm Income, Technology Adoption, and Farm Economic Performance*. USDA, ERS Research Report No. 36 (2007).
7 Fernandez-Maizeejo J and Caswell M, *The First Decade of Genetically Engineered Crops in the United States*. USDA, ERS, Economic Information Bulletin No. 11 (2006).
8 Bernard JC, Pesek JD Jr and Fan C, Performance results and characteristics of adopters of genetically engineered soybeans in Delaware. *Agric Res Econ Rev* **33**:282–292 (2004).
9 Weaver RD, Curtiss J and Brummer B, Efficiency benefits of GM technologies?: evidence from soybeans and implications for policy. *9th International Conference on Agricultural Biotechnology: Ten Years After,* ICABR (2005).
10 Marra MC, Pardey PG and Alston JM, *The Payoffs to Agricultural Biotechnology: an Assessment of the Evidence*. IFPRI, Environmental and Production Technology Division Discussion Paper No. 87 (2002).
11 USDA, *Pest Management on Major Field Crops*. AREI Updates 1997, Economic Research Service No. 1 (1997).
12 Gardner JG and Nelson CH, Genetically modified crops and labor savings in U.S. crop production. *2007 Southern Agricultural Economics Association Annual Meeting.* [Online]. Available: http://ageconsearch.umn.edu/bitstream/123456789/757/1/sp07ga01.pdf [12 December 2007].
13 Fernandez-Maizeejo J, *Farmers Balance Off-farm Work and Technology Adoption.* [Online]. Available: http://www.ers.usda.gov/AmberWaves/February07/PDF/FarmersBalance.pdf [12 December 2007].
14 Marra M and Piggott N, The value of non-pecuniary characteristics of crop biotechnologies: a new look at the evidence, in *Regulating Agricultural Biotechnology: Economics and Policy*, ed by Just RE, Alston JM and Zilberman D (Eds.) . Springer Science and Business Media, LLC, New York: pp. 145–178 (2006).
15 Young B, Changes in herbicide use patterns and production practices resulting from glyphosate-resistant crops. *Weed Technol* **20**:301–307 (2006).
16 McDougall J and Phillips M, The impact of agricultural biotechnology on the conventional agrochemical market, in *The Economic and Environmental Impacts of Agbiotech: A Global Perspective*, ed by Kalaitzandonakes N. Kluwer Academic/Plenum Publishers, New York, NY (2003).
17 *Commodity Costs and Returns: U.S. and Regional Cost and Returns.* [Online]. SDA. Available: http://www.ers.usda.gov/Data/CostsAndReturns/ [12 December 2007].
18 Gianessi LP, Silvers CS, Sankula S and Carpenter JE, *Plant Biotechnology: Current and Potential Impact for Improving Pest Management in U.S. Agriculture, an Analysis of 40 Case Studies.* [Online]. Available: http://www.ncfap.org/40CaseStudies/MainReport.pdf [12 December 2007].

19 Sankula S and Blumenthal E, *Impacts on U.S. Agriculture of Biotechnology-derived Crops Planted in 2003: an Update of Eleven Case Studies.* [Online]. Available: http://croplife.intraspin.com/BioTech/paper.asp?id=52 [12 December 2007].
20 Sankula S, Marmon G and Blumenthal E, *Biotechnology-derived Crops Planted in 2004 – Impacts on U.S. Agriculture.* [Online]. Available: http://www.ncfap.org/whatwedo/pdf/2004ExecSummaryA.pdf [12 December 2007].
21 Brookes G and Barfoot P, GM crops: the global economic and environmental impact – the first nine years 1996–2004. *AgBioForum* **8**:187–196 (2005). Also available online: http://www.agbioforum.org/v8n23/v8n23a15-brookes.htm [12 December 2007].
22 Shaw D and Bray C, Foreign material and seed moisture in glyphosate-resistant and conventional soybean systems. *Weed Technol* **17**:389–393 (2003).
23 Griffin JL, Miller DK and Salassi ME, Johnsongrass (*Sorghum halepense*) control and economics of using glyphosate-resistant soybean in fallowed sugarcane fields. *Weed Technol* **20**:980–985 (2006).
24 Beets after beans, *The Sugarbeet Grower* February (2007).
25 USDA, *Crop Production: 2005 Summary*. National Agricultural Statistics Service (2006).
26 Dotray P, Transgenic cotton: where we are and where we are going? *Proc 2006 Beltwide Cotton Conferences.* [Online]. Available: http://www.cotton.org/beltwide/proceedings/2006/pdfs/2251-2251.pdf [12 December 2007].
27 Dotray P, Impact of RoundUp Ready technology on cotton production in the U.S. *Proc 2005 Beltwide Cotton Conferences*. [Online]. Available: http://www.cotton.org/beltwide/proceedings/2005/pdfs/401.pdf [12 December 2007].
28 Banerjee S, Hudson D and Martin SW, The impacts of seed and farm characteristics on cottonseed choice: a choice-based conjoint experiment in the Mississippi delta. *J Agric Appl Econ* **39**: 657–669 (2007).
29 Upadhyay B, Smith EG, Smith G, Clayton GW, Harker KN and Blackshaw RE, Economics of integrated weed management in herbicide-resistant canola. *Weed Sci* **54**:138–147 (2006).
30 *An Agronomic and Economic Assessment of GMO Canola*. [Online]. Canola Council of Canada. Available: http://www.canola-council.org/manual/gmo/gmo_toc.htm, [12 March 2007].
31 O'Donovan J, Harker KN, Clayton GW and Blackshaw RE, Comparison of a glyphosate-resistant canola (*Brassica napus* L.) system with traditional herbicide regimes. *Weed Technol* **20**:494–501 (2006).
32 Carew R and Smith E, Assessing the contribution of genetic enhancements and fertilizer application regimes on canola yield and production risk in Manitoba. *Can J Agric Econ/Revue Canadienne d'Agroéconomie* **54**:215–226 (2006).
33 Qaim M and Traxler G, Roundup Ready soybean in Argentina: farm level and aggregate welfare effects. *Agric Econ* **32**:73–86 (2005).
34 Brookes G, *The Farm Level Impact of Using Roundup Ready Soybeans in Romania.* [Online]. Available at: http://www.pgeconomics.co.uk/pdf/GM_soybeans_Romania.pdf [12 December 2007].
35 Gianessi L and Reigner N, *The Value of Herbicides in U.S. Crop Production: 2005 Update*. CropLife Foundation (2006).

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DOI: 10.1002/ps