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Economic Assessment of the Benefits of Chloro-s-triazine Herbicides to U.S. Corn, Sorghum, and Sugarcane Producers

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Abstract

U.S. crop producers derive substantial economic benefits from the chloro-*s*-triazine herbicides atrazine, simazine and propazine. These triazine herbicides generate yield gains for U.S. crop farmers, and in many cases, also reduce total costs for herbicides. Atrazine, the most widely used triazine herbicide, is the keystone of herbicide-based weed control in corn and other regionally important crops in the U.S. Corn acreage, yields and prices have increased over time so that the three-year average value of corn produced in the U.S. has increased more than 2.7 times, from $18.6 billion in 1990-1992 to $50.9 billion in 2007-2009. Over this same period, crop production practices also evolved, including the widespread adoption of transgenic crops and reduced tillage systems. Given these and other changes since previous economic assessments of the producer benefits from triazine herbicides, an update assessment seems warranted.

The primary benefit of atrazine and the other triazine herbicides to farmers is improved weed control that increases harvested yields and usually reduces costs, as alternative herbicides are less effective and/or more expensive. Based on yield loss and herbicide cost changes estimated using models, the economic value of the yield losses prevented by the triazine herbicides are estimated to range between $3.0 and $3.3 billion per year for U.S. corn, sorghum, sweet corn, and sugarcane farmers. Most of these benefits accrue to Midwestern field corn farmers using atrazine, but farmers in

other regions and growing these other crops also derive substantial benefits. The annual yield benefits and net herbicide cost savings from triazine herbicides are worth an estimated $2.36 to $2.65 billion for U.S. field corn growers, $341 million for U.S. sorghum growers, $210 million for U.S. sweet corn growers, and between $60 and $120 million for U.S. sugarcane growers.

Atrazine and the other triazine herbicides generate other types of benefits for farmers not accounted for in these reported values. Atrazine works well with other herbicides, often enhancing the value of less efficacious herbicides. Atrazine also increases the value of crop rotations by reducing weed populations and weed seed banks in crops commonly rotated with atrazine-treated crops. Atrazine also serves as an important tool for managing herbicide resistance, helping to preserve future weed control benefits for other herbicides. Finally, atrazine provides effective weed control that has aided adoption of conservation tillage and no-till systems in corn and other crops. Reducing or eliminating tillage reduces soil erosion and associated negative environmental impacts of agriculture, which improves water quality and further enhances the sustainability of U.S. crop production. Because specific dollar-denominated estimates of the value of these benefits to farmers are not included in this assessment, the estimated $3.0 to $3.3 billion in benefits per year should be considered a lower bound on the full value of the benefits generated by atrazine and the other chloro-*s*-triazine herbicides in U.S. crop production.

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1. Introduction

Atrazine was first commercially available for corn in the U.S. in 1959 (Pike et al. 2008). Since then, atrazine has become the most widely used chloro-*s*-triazine herbicide in the U.S. and the most commonly used corn herbicide for many years, only recently surpassed by glyphosate (Figure 1). Atrazine is the keystone of herbicide-based weed control in corn and crops such as sorghum, sweet corn and sugarcane, and by far the most popular triazine herbicide used on corn in the U.S. Propazine is used on sorghum acres. Simazine is used on corn and sweet corn acres and for weed control in many specialty crops such as citrus, grapes and other fruits and nuts (LeBaron et al. 2008).

Economic assessments of the benefits of atrazine have been part of the research and debate surrounding atrazine. Several studies have examined the farm-level economics of atrazine or have analyzed benefits at larger scales, holding crop prices and acres fixed (Hawkins et al. 1977; Martin et al. 1991; Pike et al. 1994; Swinton et al. 1994; Johnson et al. 2000; Ferrell and Witt 2002; Nolte and Young 2002; US EPA 2002). In order to assess the market-level benefits of atrazine and triazine herbicides, a few studies also included grain supply changes to account for price effects. Carlson (2008) summarized previous comprehensive national or regional economic assessments of the benefits of atrazine and triazine herbicides, but these studies are older, with the most recent published in 1998.

Though more than a decade has passed since these economic assessments were published, they are still in use, despite large increases in planted corn acreage, yields and prices. For example, Ackerman (2007) used the 1994 USDA report of

Ribaudo and Bouzaher (1994) as part of the evidence in an assessment of the economic impacts of an atrazine ban in the U.S. However, the overall economic size of the corn market has increased tremendously since the early 1990s. The three-year average of corn acres planted for 1990-1992 was 76.5 million acres, while the average was 88.6 million acres for 2007-2009, or an increase of 16% (USDA-NASS 2011). Yields also increased – the three-year average corn yield per harvested acre was 119.5 bu for 1990-1992 and 156.4 for 2007-2009, or 31% greater (USDA-NASS 2011). Average prices received by farmers also increased. The three-year average corn price was $2.24/bu for 1990-1992 and $3.94/bu for 2007-2009, a 76% increase (USDA-NASS 2011). All combined, the three-year average total production of corn in the U.S. increased from 8.3 billion bushels to 12.7 billion bushels (54%) over the same period, and the three-year average market value of this production increased 170%, from $18.6 billion to $50.2 billion over the same period. Simply adjusting older estimates of the benefits of triazine herbicides for inflation ignores this expansion in the size of the corn market and underestimates their benefits. Thus by itself, the large expansion of the corn market implies that previous economic assessments of the benefits of triazine herbicides are likely outdated.

Other trends also imply that previous benefits assessments may no longer be accurate for current market and production conditions. Genetically engineered crops were first commercialized in 1995 and have become widely adopted since then. For example, 86% of U.S. corn acres in 2010 were planted in some type of transgenic seed (USDA-ERS 2011a). Indeed, glyphosate-tolerant crops have become so popular among farmers that in 2007 glyphosate surpassed atrazine as the most widely used corn herbicide (Figure 1) (USDA-ERS 2011a). However, glyphosate-resistant weeds now threaten the efficacy of glyphosate, with many farmers aware of the problem and concerned about herbicide resistant weeds (Johnson et al. 2009; Powles 2008; Hurley et al. 2009b). In addition, the biofuel industry has become much larger since these previous studies were completed, causing various adjustments in the agricultural sector as a result of higher demand for corn (Westcott 2007; Larson et al. 2010; Gehlar et al. 2010).

As a result, previous economic assessments of the benefits of atrazine and triazine herbicides are outdated. This paper provides an updated economic assessment of the current benefits of the triazine herbicides to U.S. producers. Similar to previous studies, a counterfactual approach is used that specifies how crop production would change if triazine herbicides were not available as a non-triazine scenario, and then differences between this scenario and a baseline scenario are used to estimate the economic benefits of triazine herbicides to U.S. producers.

2. Status quo and non-triazine scenarios

The approach used here defines a baseline scenario, called the “status quo” scenario, and two “non-triazine” scenarios, and then calculates differences between the non-triazine and the status quo scenarios to estimate how the agricultural economy would change if either of these non-triazine scenarios were realized. The analysis uses the three-year average for 2007-2009 for variables such as planted area, yields, and prices to smooth over annual variation, so that the base period for the status quo scenario is 2007-2009. For crops, the analysis examines corn, sorghum, sweet corn, and sugarcane. Under the non-triazine scenarios, atrazine and simazine are not available for use on field corn and sweet corn, atrazine and propazine are not available for use on sorghum, and atrazine is not available for use on sugarcane.

Glyphosate is the most widely used herbicide on corn in the U.S., applied to 75% of planted acres in 2009 (Figure 1). Thus, if atrazine and simazine were not available for weed control in corn, an increase in the percentage of corn acres treated with glyphosate seems likely, but how much is unclear. To bracket the range of likely farmer responses, two non-triazine scenarios are defined to reflect different assumptions regarding how much farmers increase glyphosate use on field corn if triazine herbicides are not available, following the projections of Bridges (2011).

The first non-triazine scenario, "increasing glyphosate use on corn acres," assumes that if atrazine and simazine were not available, farmers switch to using glyphosate as a substitute herbicide. As a result, corn acres treated with glyphosate increase, actually projected to reach 100% in all but one region. The second non-triazine scenario, "2009 glyphosate use on corn acres," assumes that, even if atrazine and simazine were not available for weed control in corn, farmers switch to non-triazine herbicides other than glyphosate as substitutes. As a result, the percent of corn acres treated with glyphosate equals the percent in 2009, but the percent of acres treated with other non-triazine herbicides increases. These two scenarios are intended to bracket the likely response of U.S. corn farmers if atrazine and simazine were not available. Note that for sorghum, sweet corn and sugarcane, only a single non-triazine scenario is defined, a scenario that assumes atrazine and simazine are not available for sweet corn, atrazine and propazine are not available for sorghum, and atrazine is not available for sugarcane.

3. Widespread use of atrazine as evidence of its value

Atrazine is a low-cost and highly effective herbicide for controlling many broadleaf and several grass weeds. As a result, atrazine has been a primary component of herbicide-based weed control tactics in U.S. crop production for about 50 years, particularly for corn. USDA data show that the percentage of U.S. corn acres receiving some form of atrazine ranged between 62%-75% of planted acres from 1990 to 2005 and only began to decrease with the rising popularity of glyphosate tolerant corn (Figure 1). At typical single-application rates, atrazine and glyphosate typically cost less than other relatively popular single-compound grass herbicides such as acetochlor, *S*-metolachlor and nicosulfuron , and the broadleaf herbicide mesotrione, and provide more effective control of many broadleaf weed species (Zollinger et al. 2010; Hager 2010). However, in 2009, even after herbicide-tolerant corn adoption had reached 68% and glyphosate use had increased so that more than 75% of corn acres received glyphosate, 57% of corn acres still received an atrazine-containing product (Figure 1) (USDA-NASS 2010). Even with the widespread adoption of herbicide-tolerant crops and with low-cost glyphosate available, these adoption rates show that U.S. corn farmers still find value in atrazine.

This widespread use of atrazine for weed control in corn is evidence that farmers continue to derive economic benefits from its use. Atrazine is also by far the most commonly used herbicide for other regionally important crops, such as sorghum, sweet corn and sugarcane. This reliance on atrazine in these crops is further evidence that farmers also derive economic benefits from it.

The Agricultural Chemical Use Database provides herbicide use data for sorghum and sweet corn, and for both crops, atrazine is the most commonly used herbicide (USDA-NASS 2010). Sorghum data are reported only for 1991 and 2003, when 11.1 million and 9.4 million acres of sorghum were planted in the U.S., respectively (USDA-NASS 2011). In 1991, 68% of the acres were treated with atrazine; the second most commonly used herbicide (metolachlor) was used on 20% of acres (USDA-NASS 2010). In 2003, 70% of sorghum acres were treated with atrazine and the second most commonly used herbicide was glyphosate used on 27% of sorghum acres as a burndown treatment. (USDA-NASS 2010).

The database includes separate herbicide use data for fresh and processed sweet corn, biennially from 1992 to 2006 (USDA-NASS 2010). USDA acreage data are not available for this whole period, but from 1998 to 2006, planted acres for fresh market sweet corn remained steady at about 250,000 acres, while acres of sweet corn for processing (canned and frozen) declined 20%, from almost 500,000 acres in 1998 to about 400,000 acres in 2006 (USDA-NASS 2011). Figure 2 shows that from 1992 to 2006, the percent of sweet corn acres treated with atrazine generally trended upwards, rising from around 50% in 1992 to about 60% to 70% in 2006. For both types of sweet corn, atrazine was by far the most commonly used herbicide, consistent with the survey findings of Williams et al. (2010). Over these years, on average, sweet corn planted acres treated with atrazine exceeded acres treated with any other herbicide by at least 27 percentage points (USDA-NASS 2010).

Atrazine is also widely used for weed control in sugarcane, while simazine is commonly used on other specialty crops such as citrus (Smith et al. 2008; Singh and

Sharma 2008; Elmore and Lange 2008). Sugarcane harvested acreage has ranged from about 800,000 acres in 1990 to a peak of more than 1 million acres in 2000 and 2001; in recent years, sugarcane harvested acres have held steady at about 875,000 acres (USDA-NASS 2011). Most (93%) of this acreage is in Florida and Louisiana, with the remainder in Texas and Hawaii. Herbicide use data for Florida, Louisiana and Texas show that in 2009, atrazine was used on 57% of harvested sugarcane acres, making it the most commonly used sugarcane herbicide (GfK Kynetec 2010). However, regional differences exist, e.g., Florida has a much higher percent use of atrazine in sugarcane than Louisiana. In these three states, the next most commonly used herbicides were 2,4-D and metribuzin, each used on substantially fewer acres: 42% and 39% of harvested acres, respectively.

4. Weed control benefits of atrazine

This assessment required estimates of the expected yield and cost effects of using substitute herbicides if U.S. farmers could not use atrazine or the other chloro-*s*-triazine herbicides for weed control. This analysis uses the estimated yield loss and cost effects reported by Bridges (2011) for both non-triazine scenarios for corn (increasing glyphosate acres and 2009 glyphosate acres) and for the single non-triazine scenarios for sorghum and sweet corn. Because comparable estimates do not exist for sugarcane, this analysis uses estimates of the expected yield and cost effects from local experts (see footnotes to Table 1).

Bridges' (2011) estimates for corn, sorghum and sweet corn were developed based on 2009 regional data on weed infestations, potential yield losses and herbicide efficacies, all by weed species, and crop yield potential in the production regions.

Harvested yields and net returns were estimated by region for various herbicide treatments using 2009 treatment costs and the regional data for weed infestations, losses and herbicide efficacies. The analysis did not include cost and yield impacts for acres currently treated with simazine switching to non-triazine substitutes. Regional average net returns were determined based on the 2009 percent of acres treated by each herbicide treatment. The impact of atrazine and the other triazine herbicides on crop yields and costs was estimated by comparing regional average net returns under 2009 treatment practices to the two non-triazine scenarios. The final results reported in Table 1 are Bridges' (2011) estimates of how much regional average corn, sorghum, and sweet corn yields would decrease and weed control costs would change if chloro-*s*-triazine herbicides were not available. These yield loss and cost changes are averages, spread over all acres of each crop, not just those acres treated with a triazine herbicide.

In Table 1, separate results for corn are reported for the four USDA Farm Resource Regions[a] that encompassed over 90% of corn production in 2009, with the remaining regions combined into a single "Rest of Nation" region to simplify the analysis. For the non-triazine scenario with increasing glyphosate use on corn acres, Bridges (2011) estimated greater yield losses and cost increases in the Heartland than the other three regions. For the non-triazine scenario with 2009 glyphosate use on corn acres, because acres treated with glyphosate do not increase, estimated yield losses are greater due to farmer reliance on less efficacious herbicides. However, estimated

[a] The USDA-Economic Research Service defined these Farm Resource Regions by clustering counties based on a variety of characteristics (USDA-ERS 2000). The resulting regions cut across state lines and include the Heartland, Northern Crescent, Northern Great Plain, Prairie Gateway as the main corn producing regions, as well as the Eastern Uplands, Southern Seaboard, Basin and Range, Mississippi Portal and Fruitful Rim. For more detail, see the map included in the publication (USDA-ERS 2000).

net herbicide cost effects are negative (i.e., a cost decrease) or smaller than for the other corn non-triazine scenario.

Bridges' (2011) estimates for sweet corn in Table 1 show an estimated yield loss of approximately 20% for the regions examined (Heartland, Northern Crescent, Fruitful Rim), with the estimate for the Rest of Nation simply the average for the other regions. Sweet corn yield and quality generally exhibit greater sensitivity to weed interference, and relatively high weed populations remain in Midwestern sweet corn fields even though most acres receive herbicide treatments, plus fewer registered herbicides are available, particularly effective non-triazine alternatives for problematic weed species (So et al. 2009; Tracy 2001; Williams et al. 2008; Elmore and Lange 2008). Estimated herbicide cost changes are comparable to those for field corn, but negative (i.e., a cost decrease) in the Northern Crescent because farmers switch to lower cost and/or less effective herbicides for the non-triazine scenario. As no herbicide cost change was available for the Rest of Nation region, the analysis assumes no cost change for this region. Finally, because glyphosate-tolerant sweet corn is commercially unavailable, only a single non-triazine scenario was developed.

Bridges (2011) developed the results in Table 1 for sorghum based on data for the Prairie Gateway, the region producing 74% of U.S. sorghum in 2009, and then used these yield loss and cost impacts for all regions. Results show an estimated yield loss of more than 20% for sorghum because fewer registered herbicides are available, particularly effective non-triazine alternatives for problematic weed species. Estimated cost changes are negative (i.e., a cost decrease) because farmers switch to lower cost and/or less effective herbicides for the non-triazine scenarios. Finally, because glyphosate-tolerant sorghum is unavailable, only a single non-triazine scenario was developed.

For sugarcane, the necessary data were not available to conduct an analysis and estimation process comparable to Bridges (2011). Hence, local experts (see footnotes to Table 1) in the main producing regions were contacted to informally survey major growers in their regions to ask them to use their experience in sugarcane production to estimate yield and cost effects if atrazine were not available. Yield loss estimates ranged from 10% to 25% in the Fruitful Rim (Florida and Texas) and from 20% to 25% in the Mississippi Portal (Louisiana). The average cost change in the Fruitful Rim was about a $5/ac cost decrease as growers switched to less costly and/or less effective alternative herbicides, while in the Mississippi Portal, the average cost increased more than $4/ac. In Hawaii, the 6% average yield loss is based on grower estimates of 10% of the acres suffering a 60% yield loss; however, no herbicide cost change estimate was available, so the analysis assumes no cost change.

Finally, note that the yield losses and cost changes reported in Table 1 are average changes at the aggregate level that are spread over all planted acres and the cost changes do not include additional costs for extra passes to apply herbicides, only the net change in the cost of herbicide active ingredients. When averaging over producers to determine an aggregate change, the resulting average misses the range of individual effects. Some farmers would see large cost changes under a non-triazine scenario as they shift to more costly substitute herbicides to control the problematic weed species, and even then, they would suffer yield losses larger than average used for this analysis. Other farmers would be able to use low-cost alternatives and actually see a cost decrease and suffer yield losses less than the average assumed for this analysis because of the weed species prevalent in their area. Furthermore, these average yield loss and cost changes are spread over all acres for each crop, not just those acres currently treated with triazine herbicides. For example, if the 60% of crop acres currently using atrazine switched to herbicides that on average cost $10 per acre more, the average cost change when spread over all crop acres would be $6 per acre. As a result, the average changes in Table 1 are smaller than the average changes for farmers currently using triazine herbicides and miss the range of individual yield losses and cost changes that would occur if triazine herbicides were not available.

5. Value of triazine weed control benefits to producers

Per acre yield losses and cost increases in Table 1 were aggregated over planted acres to estimate the short-term total losses to U.S. producers under the non-triazine scenarios relative to the status quo base case. For corn, sorghum, sweet corn and sugarcane, three-year averages for 2007-2009 were used based on USDA data for yields, prices and planted acres. Because of the relationship between yields and prices, three-year averages of per acre crop values (yield multiplied by price) were used, not the three-year average of yield multiplied by the three-year average of price. Thus, in these tables, the product of the three-year average yield and the three-year average price does not exactly equal the three-year average crop value.

For corn and sorghum, yield and price data for 2007-2009 are from the USDA-ERS Commodity Costs and Returns Data for each Farm Resource Region (USDA-ERS 2011b). For other regions, USDA-ERS (2011b) corn data are only available for the Eastern Uplands and the Southern Seaboard, so the acreage-weighted average of data for these two regions is used for the Rest of Nation. Similarly, for sorghum, the Rest of Nation uses the acreage-weighted average of USDA-ERS (2011b) data for the Heartland, Northern Great Plains and Fruitful Rim. The average number of acres of corn and sorghum per farm is also reported in order to calculate average losses and cost changes per farm. Total U.S. acreage for corn, sorghum, sweet corn and sugarcane is from USDA-NASS (2011). The sweet corn and sugarcane analysis only uses these national acreage data, as detailed data comparable to the USDA-ERS (2011b) data for corn and sorghum are not available by region for these crops.

Table 2 reports results for corn. The acreage and crop value data show that more than half of U.S. corn acres and the crop value are in the Heartland, with more than 52 million acres planted and producing a crop worth almost $31 billion. The Northern Crescent and Prairie Gateway each have around 11 million acres, but the total value of the crop is larger in the Prairie Gateway because average yields and prices are higher. The average number of corn acres planted per farm is also noticeably larger in the Northern Great Plains and the Prairie Gateway.

As expected, annual average yield losses per acre of corn under the non-triazine scenarios is larger for the 2009 glyphosate acres scenario than the increasing glyphosate acres scenario. Revenue losses are generally larger in the Heartland, more than $31/ac for the increasing glyphosate acres scenario and more than $36/ac for the 2009 glyphosate acres scenario. Revenue losses for the Rest of Nation are large for the second non-triazine scenario because percentage losses for the region are quite large in Table 1. Revenue losses in the other regions are relatively lower because of the lower percentage losses in Table 1 for the non-triazine scenarios. Average revenue losses per farm vary across regions because both the average revenue losses per acre and the average number of corn acres per farm differ across regions. Average annual revenue losses per farm were largest in the Heartland, at almost $9,000 for the first non-triazine scenario and at more than $10,000 for the second non-triazine scenario, based on an average of 281 corn acres per farm in the Heartland (Table 2).

Aggregating these yield losses shows that 70% to 75% of the total losses occur in the Heartland, where per acre losses are highest and most corn acres are planted. Losses to U.S. producers total almost $2.2 billion per year for the increasing glyphosate acres scenario and almost $2.7 billion for the 2009 glyphosate acres scenario, with $1.6 and $1.9 billion of these losses occurring in the Heartland. Aggregate losses for producers in the other regions are millions of dollars per year and all together account for about 25% to 30% of total U.S. losses. These results show that atrazine is a key part of weed control in corn, annually preventing yield losses worth about $2.2-$2.7 billion, and that it is especially valuable in the Heartland where most U.S. corn is grown.

Table 2 also reports both per farm and aggregate U.S. producer costs based on the herbicide cost changes in Table 1 for the non-triazine scenarios. For the increasing glyphosate acres scenario, herbicide costs increase in all regions, with the average annual cost increase per farm as high as $750 in the Heartland. In aggregate, the total increase in herbicide costs would total about $177 million per year, with almost 80% of this cost increase born by farmers in the Heartland. For the 2009 glyphosate acres scenario, farmers in some regions would see an herbicide cost decrease as they switched to cheaper and/or less effective herbicides to substitute for atrazine, while costs would increase in other regions. The largest savings in herbicide costs occur in the Northern Crescent, while the largest cost increase occurs in the Northern Great Plains. In aggregate, the total herbicide cost change is a net decrease of $43 million per year for the whole U.S., with most of this occurring in the Northern Crescent and the Heartland.

Finally, Table 2 aggregates these yield losses and cost changes by region and for the whole U.S. to determine the net income effect. The impacts on net income are largest in the Heartland, where the average net loss per acre is about $34 to $36/ac and the average net loss per farm is around $10,000. Aggregating losses over all regions gives a net income loss of $2.36 billion to $2.65 billion per year for U.S. corn producers, with 70% to 75% of this loss occurring in the Heartland.

The results in Table 2 are calculated using the regional-specific corn yields and prices reported in Table 2. These yields and prices are the three-year average of yields and prices for 2007-2009 as reported in USDA-ERS regional crop budgets (USDA-ERS 2011b), while the U.S. average yield and price reported in Table 2 is the average for the five regions, weighted by the total acres in each region. As a result, the yields and prices in Table 2 are lower than the USDA-NASS yields and prices. For example, the three-year (2007-2009) average corn yield for the U.S. is 156.4 bu/ac based on USDA-NASS (2011) data, but 145.5 bu/ac based on the USDA-ERS (2011b) data and weighting by acres. Similarly, the three-year (2007-2009) average corn price for the U.S. is $3.94/bu based on USDA-NASS (2011) data, but $3.76/ac based on the USDA-ERS (2011b) data and weighting by acres. Based on these results, the per-acre revenue for corn is 145.5 x $3.76 = $547.08 using the USDA-ERS data and, using the USDA-NASS data, 156.4 x $3.94 = $616.22, or 12.6% larger. These results imply that the USDA-ERS data provide more conservative estimates of the revenue and incomes changes for the non-triazine scenarios analyzed.

The results in Table 2 would change under different corn yield and price assumptions. For the non-triazine scenarios in Table 2, higher corn yields and prices only impact the revenue changes, not the cost changes. As revenue is proportional to both yield and price, a 33% increase in either yield or price implies a 33% increase in the revenue changes. However, because the cost changes in Table 2 are relatively small compared to the revenue changes, a 33% increase in yield or price implies approximately a 33% increase in the net income changes. Using a specific example to illustrate, increasing corn prices by 33% gives a U.S. corn price of $5.00/bu. The associated net income changes for the non-triazine scenarios are a net loss of $3.08 to $3.54 billion, or 30.5% to 33.5% larger than the $2.36 to $2.65 billion reported in Table 2. Thus, because the 2010 season-average corn price of $5.40 is 44% larger than $3.76, the results in Table 2 would roughly be 44% larger using a corn price of $5.40/bu (USDA-NASS 2011).

Table 3 reports results for sorghum, but only with the Prairie Gateway and the Rest of Nation. The average value of all sorghum grown in the U.S. has averaged about $1.8 billion per year, with more than 70% of the value originating in the Prairie Gateway region. Only a single non-triazine scenario is examined for sorghum as herbicide-tolerant sorghum is not available. Average revenue losses per acre for sorghum range from $43 to $47 per year if atrazine and propazine were not available. Per acre losses are larger than for corn because sorghum yield losses are generally much larger (Table 1). On a per farm basis, average revenue losses range from more than $12,500 in the Prairie Gateway to about $26,000 in the Rest of Nation, based on the average sorghum acres per farm as reported in Table 3. Farm-level losses are much larger than for corn farmers because per acre losses are larger and the average number of sorghum acres per farm is much larger in the Rest of Nation. Aggregating the values of these yield losses, total revenue losses for U.S. sorghum producers is $364 million annually, with $260 million (71%) occurring in the Prairie Gateway.

Table 3 also reports the resulting herbicide cost changes for the non-triazine scenario. Herbicide costs decrease for sorghum producers as farmers switch to lower cost and/or less effective herbicides without atrazine or propazine, so that in aggregate, total cost savings amount to almost $24 million per year for U.S. sorghum producers.

The final rows of Table 3 combine these revenue losses and cost changes to estimate the net total effect for U.S. sorghum producers. The annual net income loss is about $44/ac and almost $12,000 per farm in the Prairie Gateway, based on an average of 269 sorghum acres per farm in the region. Producers in other regions have smaller per acre net income losses of about $40/ac, but much larger average losses per farm of more than $24,000, based on an average of 608 sorghum acres per farm. In aggregate, total income loss for U.S. sorghum producers is $341 million each year, with $243 million (71%) of this loss occurring in the Prairie Gateway.

The effect of using a different sorghum price would be the same as for corn – only the revenue effects would change, not the cost effects, and net income changes would be approximately the same in percentage terms as the price change. Thus a 33% increase in the sorghum price to give a U.S acreage-weighted average of $4.72/bu would increase the net income effects to $461 million, or 35.3% larger than in Table 3.

Table 4 reports regional and total U.S. losses for fresh and processing sweet corn for the non-triazine scenario based on USDA-ERS (2010b) sweet corn acreage and price data and yield loss and herbicide cost changes in Table 1. Average yields are greatest in the Fruitful Rim and the Rest of Nation, where most of the acres are grown, especially fresh sweet corn, while the Heartland and Northern Crescent have sizeable production of processing sweet corn. The average value of the fresh crop is almost $750 million, and about $300 million for the processed sweet corn crop, for a total annual average crop value of more than $1 billion for all sweet corn grown in the U.S.

Table 4 shows greater losses under the non-triazine scenario for the relatively higher-valued fresh sweet corn than for processed sweet corn. Losses for fresh sweet corn range from more than $800/ac in the Fruitful Rim to around $450/ac in the Heartland, with an acreage-weighted average loss of almost $600/ac for the U.S. For processed sweet corn, losses range from a high of almost $200/ac in the Fruitful Rim to around $140/ac in the other regions, with an acreage-weighted average loss of almost $160/ac for the U.S. In aggregate, total annual losses are $210 million, or 20% of the value of the annual U.S. crop, with almost three-fourths of these losses occurring for fresh-market sweet corn growers. Across the regions, almost half of these losses are born by growers in the Fruitful Rim, where both per acre losses and total planted acres are greatest. Total annual losses in the Northern Crescent are $54 million, or more than 25% of the total U.S. losses. Changes in average herbicide costs are less than $0.60 per acre when spread over all sweet corn acres.

Table 5 reports regional and total U.S. losses for sugarcane for the non-triazine scenario based on USDA-ERS (2010a) data on acres and prices and the yield loss and herbicide cost changes in Table 1. Hawaii has much larger sugarcane yields than other producing regions, but far fewer harvested acres. In total, the U.S. annual sugarcane harvest is worth $918 million on average. More than half of this crop value is produced in Florida, which dominates the Fruitful Rim crop value of $489 million. Only 5% or $49 million of the crop value is produced in Hawaii, with Louisiana and Texas in the Mississippi Portal producing the remaining 41% or $380 million.

Based on the low and high estimates of yield losses in Table 1 for sugarcane, Table 5 reports the resulting per acre value of these yield losses for the non-triazine scenario. Using the low yield loss estimates, annual losses range from about $110/ac in the Fruitful Rim to more than $180/ac in the Mississippi Portal. Using the high yield loss estimates, annual losses range from $130/ac in Hawaii to more than $280/ac in the Fruitful Rim. Losses are lower in the Fruitful Rim and Hawaii because of generally lower pressure from weeds that currently are managed with atrazine. Based on affected acres in each state (acres treated with atrazine), these per acre losses range from a total of $2.3 million in Hawaii to almost $90 million under the high yield loss case in the Fruitful Rim. Aggregating across all states, total losses for U.S. producers are more than $60 million per year for the low yield-loss case and more than $120 million per year for the high yield-loss case.

Herbicide cost changes for sugarcane ranged from over a $4/ac increase in the Mississippi Portal to a $5/ac decrease in the Fruitful Rim as a result of using herbicides other than atrazine. No herbicide cost change information was available for Hawaii. Aggregating these cost changes to all U.S. treated acres results in a $1.1 million net decrease in herbicide costs. Combining these herbicide cost changes with the much larger yield loss effects results in a net loss to U.S. sugarcane producers of almost $60 million per year for the low yield loss case and almost $120 million per year for the high yield loss case, with most of these losses occurring in the Fruitful Rim, but with a substantial portion also occurring in the Mississippi Portal.

Combining results from Tables 2 through 5, Table 6 reports that total income losses for U.S. corn, sorghum, sweet corn and sugarcane producers would range from about $3.0 to $3.3 billion per year relative to the status quo baseline, indicating the magnitude of the weed control benefits U.S. farmers derive from triazine herbicides. The values of these benefits differ by region and crop. Heartland corn farmers derive more than 60% of the total benefits from triazine herbicides, or approximately $1.85 billion per year. Farmers in the Rest of Nation derive the next greatest benefit, at about $610 million annually. Growers in this combined region derive benefits from using triazine herbicides in corn, but about half of these benefits are derived from using triazine herbicides in sweet corn, sorghum and sugarcane production. Farmers in the Prairie Gateway region derive benefits of around $370 million annually from the weed control provided by triazine herbicides, with about two-thirds of the benefit in sorghum production and the remainder in corn production. Farmers in the Northern Crescent and Northern Great Plains regions derive benefits from triazine herbicides primarily in corn production, with their portions together constituting about 10% of the total economic benefit for U.S. growers, or around $320 million per year.

These results do not account for a variety of other important benefits the producers derive from atrazine and the other triazine herbicides. The next sections of this paper will provide an overview of some of these other benefits, with some illustrations of their possible magnitude. Hence, the values reported in Table 6 should be considered lower bound estimates of the economic benefits that U.S. producers derive from atrazine and the other triazine herbicides. Thus, the triazine herbicides are worth at least $3.0 to $3.3 billion per year to these crop producers as the three year average for 2007-2009. Because corn and other crop prices have recently been substantially higher than their levels in 2007-2009, we also described the effects of using different crop prices. Because revenue is proportional to the crop price and herbicide cost changes are a relatively small part of the overall benefit of triazine herbicides, assuming higher crop prices would increase these benefits roughly by the same proportion that prices are increased. Thus, if crop prices were increased by 33%, the benefits in Table 6 would be about 33% higher.

6.1 Enhancing and/or complementing other herbicides

Atrazine is commonly sold in prepackaged formulations with several other herbicides, which is partly why such a large proportion of corn acres receive atrazine in some form (LeBaron et al. 2008; Zollinger et al. 2010). Often these other herbicides are generally less effective than atrazine on certain problematic weed species, more costly and may cause more crop injury (Bridges 2008). For example, Hager (2010) reports efficacy ratings for soil-applied and foliar-applied herbicides for controlling various grass and broadleaf weed species common in Illinois corn. These efficacy ratings for foliar-applied atrazine, bromoxynil and bromoxynil + atrazine, or for soil-applied atrazine, acetochlor and acetochlor + atrazine show how bromoxynil and acetochlor become more effective and more valuable herbicides with the addition of atrazine (Hager 2010). Atrazine enhances the broadleaf spectrum of bromoxynil, and it complements the grass control of acetochlor, where atrazine provides the broadleaf control. Hager (2008) provides a summary of herbicide efficacy data from several North Central states to show that this relationship does not just occur in Illinois. In addition, increased weed control has been found when atrazine and mesotrione are applied after planting (Abendroth et al. 2006; Sutton et al. 2002). Atrazine enhances the broadleaf weed control value of other less efficacious herbicides and complements the efficacy of grass herbicides, which generates economic benefits for crop farmers.

6.2 Improved weed control in rotated crops

The weed control benefits of atrazine reach beyond its direct use on corn, sorghum, sweet corn and sugarcane. Improved weed control resulting from atrazine use in these crops reduces weed problems for crops rotated with them, crops that often have fewer herbicide options. For example, the corn-soybean rotation is common in the Midwestern U.S. and the U.S. is a major world producer of both crops, yet there are noticeably fewer herbicide options for soybeans. The Agricultural Chemical Use Database (USDA-NASS 2010) shows 46 corn herbicides were used on sufficient acres to be included in the national data set, but only 25 for soybeans. Atrazine cannot be used on soybeans, but by providing effective weed control in corn, atrazine reduces the weed seed bank and subsequent interference pressure from weed species that can be difficult to control in soybeans (Kruger et al. 2009).

This rotational use of atrazine also occurs in other crops. For example, Williams et al. (2010) find that farmers growing sweet corn following vegetable crops (peas, lima beans, snap beans, cabbage) commonly use atrazine to address higher weed infestations that occur in sweet corn grown after these crops, since fewer effective herbicides are available for vegetable crops. Without atrazine for use in sweet corn, farmers growing these and other vegetable crops would face greater weed pressure when they rotate to them, which would reduce harvested yields and/or increase weed control costs. The implication is that by reducing weed populations and resulting weed seed banks, atrazine increases the value for crops commonly rotated with corn, sorghum, sweet corn and sugarcane.

6.3 Promotion of herbicide resistance management

Atrazine improves herbicide-resistant weed management by providing a low cost and effective alternative mode of action to glyphosate and other non-triazine herbicides in corn (Owen 2011). Herbicide resistance in weed populations is a problem for most classes of herbicides and has become a serious problem in many areas of the U.S. where growers have relied heavily on glyphosate and herbicide-tolerant crops (Givens et al. 2011; Johnson et al. 2009; Heap 2010; Powles 2008). Maintaining the availability of atrazine as an alternative mode of action is particularly important for herbicide resistance management since no new herbicide modes of action have been released for agronomic grain crops since 1990 (Johnson et al. 2009). New incentive programs sponsored by Monsanto and recent research indicate that herbicide-resistant weeds are a concern among farmers and companies and impose costs that in aggregate can become substantial.

For the 2010 season, Monsanto introduced incentive programs to help farmers manage herbicide resistance. Farmers received rebates to incorporate herbicides besides glyphosate into their weed control program for Roundup Ready® cotton and soybeans, including herbicides not sold by Monsanto. Maximum rebates for cotton were $12.50/ac in 2010 and increased to $20/ac in 2011; rebates for soybeans will be as much as $3/ac in 2011.[b] In 2009, 93% of U.S. soybean acres and 78% of U.S. cotton acres were planted with herbicide-tolerant varieties, mostly Roundup Ready® (USDA-ERS 2011a). Even if only 10% of farmers using Roundup Ready® cotton and soybeans qualified for the maximum payments, based on 2010 planted acres and these adoption rates, total payments for 2011 would be almost $39 million—more than $17 million for cotton and almost $22 million for soybeans. The potential magnitude of these payments, the large increase for cotton between 2010 and 2011, and the addition of soybeans in 2011 are indicative of the potential cost of glyphosate resistance to Monsanto.

The development of herbicide-resistant weeds is also a major concern for U.S. farmers. In an open-ended and unprompted survey question, about half of corn, soybean and cotton farmers mentioned herbicide resistance in weeds as their main concern (Hurley et al. 2009b; Johnson et al. 2009). Furthermore, the analysis of Hurley et al. (2009b) shows that farmers reporting concern about weed resistance to herbicides also derived lower value from herbicide-tolerant crops, on average reducing the value growers placed on herbicide-tolerant corn by $4.85/ac and on herbicide-tolerant soybeans by $3.13/ac. Using 2010 planted acres and herbicide-tolerant crop adoption rates (USDA-ERS 2011a), if 5% more corn and soybean farmers became concerned about weed resistance because triazine herbicides were not available, these average per acre reductions in value imply an annual average loss of almost $15 million for corn

[b] For cotton, see the Performance Plus program: http://www.deltaandpine.com/dp-content/files/PerformancePlusProgram.pdf and http://www.genuity.com/Libraries/PDFs/Genuity_Cotton_PFP_Flier.pdf. For soybean, see the Residual Rewards program: http://monsanto.mediaroom.com/index.php?s=43&item=888.

farmers and almost $12 million for soybeans farmers, just from an increase in concern about herbicide-resistant weeds. This 5% assumption was used for illustration; if the increase were 10%, these values would double.

The non-triazine scenarios analyzed here assume that, without atrazine and the other triazine herbicides, the development and spread of glyphosate resistance would accelerate relative to the status quo scenario. However, the direct costs of accelerated glyphosate resistance and the resulting increased concern about herbicide-resistant weeds among growers are not included in the analysis. Because atrazine helps promote weed resistance management, it reduces these costs to growers, thus providing an additional benefit not included in this analysis. Simple cost calculations based on Monsanto's new incentive programs and the reported effect of concerns about herbicide-resistant weeds suggest that these costs could be substantial. Unfortunately, little research exists estimating these costs or the benefits of improved herbicide stewardship at the aggregate level, though individual case studies exist (Hurley et al. 2009b; Marsh et al. 2006; Mueller et al. 2005; Weersink et al. 2005; Pannel et al. 2004; Orson 1999; Gorddard et al. 1995, 1996).

6.4 Increased adoption of reduced tillage

Soil erosion is among the most costly environmental impacts of agriculture in the U.S. Pimentel et al. (1992, 1995) find that soil erosion costs U.S. society $44 billion annually, with similar costs for pesticides totaling $8 billion annually. Tegtmeier and Duffy (2004) reach a similar conclusion using more recent data. With passage of the 1985 Farm Bill, conservation compliance became a requirement for farmers receiving federal commodity support payments. Conservation compliance and the overall increased understanding of the benefits of reduced tillage have been a major driver for the increase in farmer adoption of conservation tillage practices over the last several years (Esseks and Kraft 1991; Claassen et al. 2004; Knowler and Bradshaw 2007). In 2009, 88 million acres, or almost 36% of U.S. cropland devoted to major crops, used no-till systems (Horowitz et al. 2010). The impact of conservation tillage and related practices has been a substantial and continuous decline in aggregate soil erosion, with soil erosion from U.S. cropland decreasing 43% between 1982 and 2007 (USDA-NRCS 2010).

Because weeds are a major problem in conservation tillage and more so in no-till crop production, herbicides are a key component of weed control in these production systems, although total herbicide use is generally no greater than in conventional tillage systems (Buhler 1991, 1992; Gebhardt et al. 1985; Kroskinen and McWhorter 1986; Fuglie 1999). Atrazine has been extremely effective for weed control in corn and sorghum and is a major part of reduced tillage systems for rotations including these crops. Figure 3 shows the annual percentage of corn acres grown in conventional tillage, conservation tillage and no-till systems treated with atrazine from 1998 to 2009. The decreasing use of atrazine evident in Figure 1 is also apparent in Figure 3, as is the connection between reduced tillage and atrazine use. Every year, conventional tillage corn had the lowest percentage of acres using atrazine and no-till corn had the highest percentage, except in 2007 when a greater percentage of conservation tillage corn acres received atrazine than no-till acres. These data demonstrate that in corn production, atrazine is consistently used more often in reduced tillage systems than in conventional tillage systems.

Commercialization of herbicide-tolerant crops in the mid-1990s made reduced tillage systems even more economically viable, resulting in increased adoption of no-till and other reduced tillage systems. The linkage between herbicide-tolerant crops and reduced tillage has been examined by many (e.g., Frisvold et al. 2009; Givens et al. 2009; Fulton and Keyowski 1999; Ward et al. 2002; Fernandez-Cornejo and Caswell 2006). However, the connection between atrazine use and no-till corn remains largely unexplored in the context of widespread adoption of glyphosate-tolerant corn hybrids. Hence, aggregate tillage and herbicide use data are examined graphically here to identify trends and connections.

Figure 4 shows the annual percentage of U.S. corn acres under conventional tillage, conservation tillage and no-till treated with both atrazine and glyphosate from 1998 to 2009. The percentage of corn acres receiving both atrazine and glyphosate has increased continuously since 1998, following the trend in adoption of glyphosate-tolerant hybrids and increased glyphosate use illustrated in Figure 1. However, Figure 4 also shows the connection between no-till corn and atrazine, even as glyphosate-tolerant corn hybrids became widely used. Every year, a noticeably greater percentage of no-till corn acres received both atrazine and glyphosate, much higher than for conventional and conservation tillage corn. As Figure 1 shows, the vast majority of corn acres receiving glyphosate are glyphosate tolerant. Thus, Figure 4 provides evidence of the strong connection that continues to exist between atrazine and no-till corn, even in the current era of widespread adoption of glyphosate-tolerant corn.

Figure 5 shows recent national trends in crop tillage for corn, soybeans and cotton. The data show a general trend for decreasing use of conventional tillage and increased adoption of conservation tillage and no-till, which is consistent with USDA data and analysis (Horowitz et al. 2010). However, the increasing development and spread of glyphosate-resistant weeds threatens the recent high levels of conservation tillage and no-till adoption among corn, soybean and cotton farmers (Davis et al. 2009; Foresman and Glasgow 2008; Scott and VanGessel 2007). This shift toward more intensive tillage to address problems with herbicide-resistant weeds could potentially cause total soil erosion from U.S. cropland to increase, thus reversing the trend for decreasing total soil erosion that has held for almost 30 years (Marsh et al. 2006; USDA-NRCS 2010). Figure 5 also provides some evidence that a decrease in use of no-till has already begun to occur in recent years. Beginning in 2006, the percentage of no-till acres began to decrease in cotton; the same decreased adoption of no-till occurred in corn beginning in 2008 and in 2009 in soybeans. Whether these trends are statistically significant and will continue remains unclear, as does an explanation as to why these shifts are occurring.

The data summarized in Figures 3 through 6 suggest that atrazine plays a key role in farmer adoption of no-till and conservation tillage, even with the widespread adoption of glyphosate-tolerant corn hybrids. As the number of farmers contending with glyphosate-resistant weeds continues to grow, farmers will be under increasing pressure to use more intensive tillage. Indeed, aggregate tillage data suggests such a shift may already be occurring. The increase in soil erosion that would result from more intensive tillage would potentially reverse the trend of continuously declining soil erosion from U.S. cropland that has persisted for almost 30 years (Marsh et al. 2006; USDA-

NRCS 2010). Because atrazine supports the adoption of reduced tillage, particularly in corn, it contributes to reductions in soil erosion from U.S. cropland.

7. Conclusion

Atrazine forms the foundation of weed control in crops such as corn, sorghum, sweet corn and sugarcane, as demonstrated by its widespread use by U.S. farmers growing these crops. The primary benefit of atrazine to farmers is improved weed control that increases harvested yields and often saves costs, as alternative herbicides are often less effective and more expensive. Based on yield loss and per acre herbicide cost change estimates, the value of the yield losses prevented by atrazine, simazine and propazine are estimated to range between $3.0 and $3.3 billion per year for U.S. crop farmers for a 2007-2009 three-year average baseline. Most of these benefits accrue to Midwestern corn farmers, but farmers in other regions and growing other crops also derive substantial benefits. The annual yield benefits and net herbicide cost savings from triazine herbicides are worth an estimated $341 million annually for U.S. sorghum growers, $210 million for U.S. sweet corn growers and somewhere between $60 and $120 million for U.S. sugarcane growers.

The larger value for benefits estimated in this assessment relative to older assessments occurs primarily because the overall economic size of the corn market has increased since the early 1990s. Yields, planted acres and prices have increased so that the average market value of U.S. corn production increased 170% over the past two decades, from $18.6 billion in 1990-1992 to $50.2 billion in 2007-2009 (USDA-NASS 2011). These and similar trends for other crops imply that previous estimates of the benefits of triazine herbicides are seriously outdated. The economic assessment reported here has updated the analysis to more recent market conditions.

Atrazine and the other triazine herbicides generate other benefits for farmers not included in these values. Atrazine works well with other herbicides, often enhancing the value of less effective herbicides and complementing grass herbicides. Triazine herbicides also increase the value of crop rotations by reducing weed populations and seed banks in crops commonly rotated with triazine-treated crops. Atrazine also helps farmers manage herbicide resistance among weed populations. Finally, atrazine provides effective weed control that has aided adoption of conservation tillage and no-till systems in corn and other crops, thus improving water quality by reducing soil erosion and the environmental impact of agriculture, further enhancing the sustainability of U.S. crop production. Because specific dollar-denominated estimates of the value of these benefits are not developed here, the estimated value of $3.0 to $3.3 billion per year should be considered a lower bound on the full value of the benefits generated by atrazine and the other triazine herbicides in these U.S. crop production systems.

Several factors are missing from this assessment. For example, this analysis did not include the benefits simazine use on deciduous fruit and nuts or the use of triazine herbicides on other high-value minor crops and in non-crop areas. This analysis also focuses solely on crop producers and does not try to estimate the benefits of triazine herbicides to consumers and society in general. The increased crop production generated by triazine herbicides implies lower crop prices that benefit consumers of these commodities. For corn, and to some extent sorghum, the major uses are for livestock feed and ethanol, which together use about 75% of the U.S. annual corn production (USDA 2011). Thus, atrazine and the other triazine herbicides contribute to lower retail prices for beef, pork and chicken, as well for dairy products and eggs, which in aggregate can have tremendous value to consumers. Lower grain prices also benefit the development of the ethanol industry as the U.S. pursues its alternative energy goals. Finally, lower grain prices also reduce demand for land for crop production in the U.S. and around the world.

Atrazine also has environmental benefits not accounted for in this assessment. In particular, atrazine helps producers reduce soil erosion by increasing adoption of reduced tillage production systems, which generates benefits for producers and society in general (Hansen and Ribaudo 2008). Besides reducing soil erosion, less tillage also implies lower fuel consumption, both of which imply lower net CO_2 emissions (Fawcett 2007). Furthermore, lower demand for land for crop production around the world has different effects on net CO_2 emissions, depending on where in the world land is converted to crop production (West et al. 2010).

This assessment also does not include market-level effects on the cost or input side. Specifically, the cost changes in Table 1 for the non-triazine scenarios estimate the costs for herbicide substitution at 2009 prices, which likely underestimate actual cost changes. Atrazine and glyphosate currently dominate the corn herbicide market. If atrazine and the other triazine herbicides were not available, prices for other herbicides would likely increase, implying larger costs increases than reported in Table 1.

This assessment also does not include costs for transitioning to new weed management systems if triazine herbicides were not available. Such costs would include the cost of management time and labor as farmers learned to implement new weed control systems and the cost of mistakes from both unnecessary treatments and failed treatments leading to yield loss. These and similar non-price factors are important when farmers make herbicide choices and have value (Hurley et al. 2009a; Marra and Piggott 2006). Furthermore, this assessment does not include yield losses and costs for switching corn and sweet corn acres currently treated with simazine and sorghum acres currently treated with propazine to non-triazine substitutes.

Finally, the disruption costs to the crop protection industry if triazine herbicides were not available for weed control are not accounted for in this assessment. For example, such costs would include the cost of changing and replacing inventories of more than 60 products, research costs to develop new non-triazine formulations and determine their proper use, and education costs to train employees in the proper use of these new formulations. This assessment does not account for these and similar costs in the non-triazine scenarios examined, and so it underestimates the benefits of triazine herbicides.

Table 1. Regional yield and cost changes for corn, sorghum, sweet corn, and sugarcane for the non-triazine scenarios.[a]

Crop and Farm Resource Region	Non-Triazine Scenario: Increasing Glyphosate Use on Corn Acres		Non-Triazine Scenario: 2009 Glyphosate Use on Corn Acres	
Corn[b]	Yield Change	Cost Change[c] ($/ac)	Yield	Cost Change[c] ($/ac)
Heartland	-5.26%	2.66	-6.04%	-0.29
Northern Crescent	-3.45%	1.25	-5.23%	-2.56
Northern Great Plains	-1.39%	1.13	-2.27%	0.59
Prairie Gateway	-1.84%	0.26	-2.39%	-0.23
Rest of Nation	-6.24%	1.74	-9.61%	0.05

	Non-Triazine Scenario	
Sweet Corn[b]	Yield Change	Cost Change[c] ($/ac)
Heartland	-20.47%	1.86
Northern Crescent	-20.45%	-1.10
Fruitful Rim	-19.62%	0.66
Rest of Nation[d]	-20.18%	0.47
Sorghum[b]		
All Regions[e]	-20.49%	-2.99
Sugarcane		
Fruitful Rim[f]	-10% to -25%	-5.01
Hawaii[g]	-6%	----
Mississippi Portal[h]	-20% to -25%	4.28

[a]Average yield and cost change for acres treated with triazine herbicides, spread across all planted acres for each crop.
[b]Source: Bridges (2011).
[c]Cost changes do not include additional application costs, only the cost of alternative single-pass herbicide products.
[d]Yield change and cost change for Rest of Nation are the averages of changes for the other regions.
[e]Yield and cost changes estimated for Prairie Gateway and used for all regions.
[f]Information from major sugarcane producers in Florida.
[g]Personal communication, M. Nakahata, Hawaiian Commercial and Sugar Company. Aggregate 6% loss calculated as a 60% yield loss occurring on 10% of acres currently treated with atrazine. No herbicide cost change estimate available.
[h]Personal communication, W. Jackson, Louisiana Sugarcane League.

Table 2. Estimated value of corn yield losses and herbicide cost changes by region for both non-triazine scenarios

Scenario	Item	Heartland	Northern Crescent	Northern Great Plains	Prairie Gateway	Rest of Nation	U.S. Total or Average
Observed Three-Year Average (2007-2009)[a]	Average Yield (bu/ac)	160.3	116.0	130.7	140.3	111.6	145.5
	Average Price ($/bu)	3.73	3.63	3.66	3.89	4.04	3.76
	Average Corn Acres per Farm[b]	281	128	341	322	122	255
	Total Acres (millions)	52.027	11.636	6.160	10.988	8.356	89.167
	Average Crop Value ($/ac)	597.62	421.30	478.23	543.73	446.87	545.59
	Average Crop Value ($/farm)	167,930	53,926	163,078	175,080	54,525	142,972
	Total Crop Value ($ million)	30,992	4,892	2,917	5,954	3,688	48,443
Revenue Changes							
Increasing Glyphosate	Average Yield Loss ($/ac)[c]	31.43	14.53	6.65	10.00	27.88	24.54
	Average Yield Loss ($/farm)	8,833	1,860	2,267	3,221	3,402	6,269
	Total Yield Loss ($ million)	1,630	169	41	110	230	2,179
2009 Glyphosate	Average Yield Loss ($/ac)[c]	36.10	22.03	10.86	13.00	42.94	30.31
	Average Yield Loss ($/farm)	10,143	2,820	3,702	4,184	5,240	7,549
	Total Yield Loss ($ million)	1,872	256	66	142	354	2,691
Cost Changes							
Increasing Glyphosate	Herbicide Cost ($/ac)[c]	2.66	1.25	1.13	0.26	1.74	1.99
	Herbicide Cost ($/farm)	747	160	385	84	212	514
	Herbicide Cost ($ million)	138	15	7.0	2.9	15	177
2009 Glyphosate	Herbicide Cost ($/ac)[c]	-0.29	-2.56	0.59	-0.23	0.05	-0.49
	Herbicide Cost ($/farm)	-81	-328	201	-74	6.1	-85
	Herbicide Cost ($ million)	-15	-30	3.6	-2.5	0.4	-43
Net Income Changes							
Increasing Glyphosate	Average Total Loss ($/ac)	34.09	15.78	7.78	10.26	29.62	26.53
	Average Total Loss ($/farm)	9,581	2,020	2,652	3,305	3,615	6,783
	Total Loss ($ million)	1,769	183	48	112	245	2,356
2009 Glyphosate	Average Total Loss ($/ac)	35.81	19.47	11.45	12.77	42.99	29.83
	Average Total Loss ($/farm)	10,061	2,493	3,903	4,110	5,246	7,464
	Total Loss ($ million)	1,857	226	70	140	355	2,647

[a]Source: USDA-ERS (2011b).
[b]Average acres of corn planted for farms that grow corn.
[c]Based on yield loss or herbicide cost changes in Table 1.

Table 3. Estimated value of sorghum yield losses and herbicide cost changes by region for the non-triazine scenario.[a]

Scenario	Item	Prairie Gateway	Rest of Nation	U.S. Total or Average
Observed Three-Year Average (2007-2009)[b]	Average Yield (bu/ac)	66.3	56.1	63.2
	Average Price ($/bu)	3.47	3.72	3.55
	Average Sorghum Acres per Farm[c]	269	608	372
	Total Acres (millions)	5.522	2.411	7.933
	Average Crop Value ($/ac)	229.53	209.58	223.46
	Average Crop Value ($/farm)	61,743	127,623	81,764
	Total Crop Value ($ million)	1,268	510	1,778
Revenue Changes	Average Yield Loss ($/ac)[d]	47.03	42.94	45.79
	Average Yield Loss ($/farm)	12,651	26,150	16,753
	Total Yield Loss ($ million)	260	104	364
Cost Changes	Herbicide Cost ($/ac)[d]	-2.99	-2.99	-2.99
	Herbicide Cost ($/farm)	-804	-1,816	-1,112
	Herbicide Cost ($ million)	-16.5	-7.2	-23.7
Net Income Changes	Average Total Loss ($/ac)	44.04	39.95	42.80
	Average Total Loss ($/farm)	11,847	24,334	15,642
	Total Loss ($ million)	243	97	341

[a]Yield and cost changes estimated for Prairie Gateway used for Rest of Nation.
[b]Source: USDA-ERS (2011b).
[c]Average acres of sorghum planted for farms that grow sorghum.
[d]Based on yield loss or herbicide cost changes in Table 1.

Table 4. Estimated value of yield losses and herbicide cost changes by region for fresh and processing sweet corn for the non-triazine scenario.

	Fruitful Rim	Heartland	Northern Crescent	Rest of Nation	U.S. Total or Average
Fresh Sweet Corn					
Observed Three-Year Average (2007-2009)[a]					
Average Yield (cwt/ac)	154	83	85	113	115
Average Price ($/cwt)	26.78	26.99	28.73	20.36	26.00
Acres	86,600	29,700	82,667	50,833	249,800
Average Crop Value ($/ac)	4,123	2,216	2,445	2,318	2,974
Total Crop Value ($ million)	357	66	202	118	743
Revenue Change					
Average Yield Loss ($/ac)	809.01	453.66	500.04	467.84	595.09
Average Yield Loss ($ million)	70.1	13.5	41.3	23.8	148.7
Cost Change					
Herbicide Cost ($/ac)[b]	0.66	1.86	-1.10	0.47	0.18
Herbicide Cost ($ million)[b]	0.06	0.06	-0.09	0.02	0.0
Net Income Change					
Average Total Loss ($/ac)	809.67	455.52	498.94	468.31	595.27
Average Total Loss ($ million)	70.1	13.5	41.2	23.8	148.7
Processing Sweet Corn					
Observed Three-Year Average (2007-2009)[a]					
Average Yield (cwt/ac)	9.8	6.9	7.1	7.1	7.8
Average Price ($/cwt)	102.07	100.91	101.69	97.09	100.71
Acres	100,800	127,333	89,233	66,983	384,350
Average Crop Value ($/ac)	1,000.42	700.96	723.64	693.00	782.86
Total Crop Value ($ million)	101	89	65	46	301
Revenue Change					
Average Yield Loss ($/ac)	196.28	143.49	147.99	139.85	157.74
Average Yield Loss ($ million)	19.8	18.3	13.2	9.4	60.6
Cost Change					
Herbicide Cost ($/ac)[b]	0.66	1.86	-1.10	0.47	0.62
Herbicide Cost ($ million)[b]	0.07	0.24	-0.10	0.03	0.2
Net Income Change					
Average Total Loss ($/ac)	196.94	145.35	146.89	140.32	158.36
Average Total Loss ($ million)	19.9	18.5	13.1	9.4	60.9
Total Net Income Loss ($ million)	90	32	54	33	210

[a]Source: USDA-ERS (2010b).
[b]Based on yield loss or herbicide cost changes in Table 1.

Table 5. Estimated value of sugarcane yield losses and herbicide cost changes by region for the non-triazine scenario.

	Mississippi Portal	Fruitful Rim	Hawaii	U.S. Total or Average
Observed Three-Year Average (2007-2009)[a]				
Average Yield (tons/ac)	30.3	35.0	65.4	33.6
Average Price ($/ton)	29.97	32.04	33.23	31.23
Harvested Acres	416,667	434,533	22,633	873,833
Treated Acres[b]	123,283	318,959	18,000	460,242
Average Crop Value ($/ac)	910.81	1124.98	2167.05	1050.76
Total Crop Value ($ million)	380	489	49	918
Revenue Changes				
Average Loss (low) ($/ treated ac)	182.16	112.50	130.02	131.84
Average Loss (high) ($/ treated ac)	227.70	281.24	130.02	260.99
Average Loss (low) ($ million)	22.46	35.88	2.34	60.7
Average Loss (high) ($ million)	28.07	89.71	2.34	120.1
Cost Changes				
Herbicide Cost ($/ac)[c]	4.28	-5.01	0.00	-2.33
Total Herbicide Cost ($ million)	0.53	-1.60	0.00	-1.1
Net Income Changes				
Average Total Loss (low) ($ million)	22.99	34.28	2.34	59.6
Average Total Loss (high) ($ million)	28.60	88.11	2.34	119.0

[a]Source: USDA-ERS (2010a).
[b]Acres treated with atrazine based on 2009 data from GfK Kynetec (2010).
[c]Based on herbicide cost changes in Table 1.

Table 6. Summary of average total annual income losses ($1,000,000) for U.S. producers by crop and region for the non-triazine scenarios.

Crop	Heartland	Northern Crescent	Northern Great Plains	Prairie Gateway	Rest of Nation	U.S. Total
Corn						
Glyphosate Acres[a]						
Increasing	1,769	183	48	112	245	2,356
2009	1,857	226	70	140	355	2,647
Sorghum	---	---	---	243	97	341
Sweet Corn	32	54	---	---	123	210
Sugarcane						
Yield Loss						
Low	---	---	---	---	60	60
High	---	---	---	---	119	119
U.S. Total (low)	1,801	238	48	356	525	2,966
U.S. Total (high)	1,889	280	70	383	694	3,316

[a]Values for the non-triazine scenario with increasing glyphosate use on corn acres (Increasing) and for the non-triazine scenario with 2009 glyphosate use on corn acres (2009).

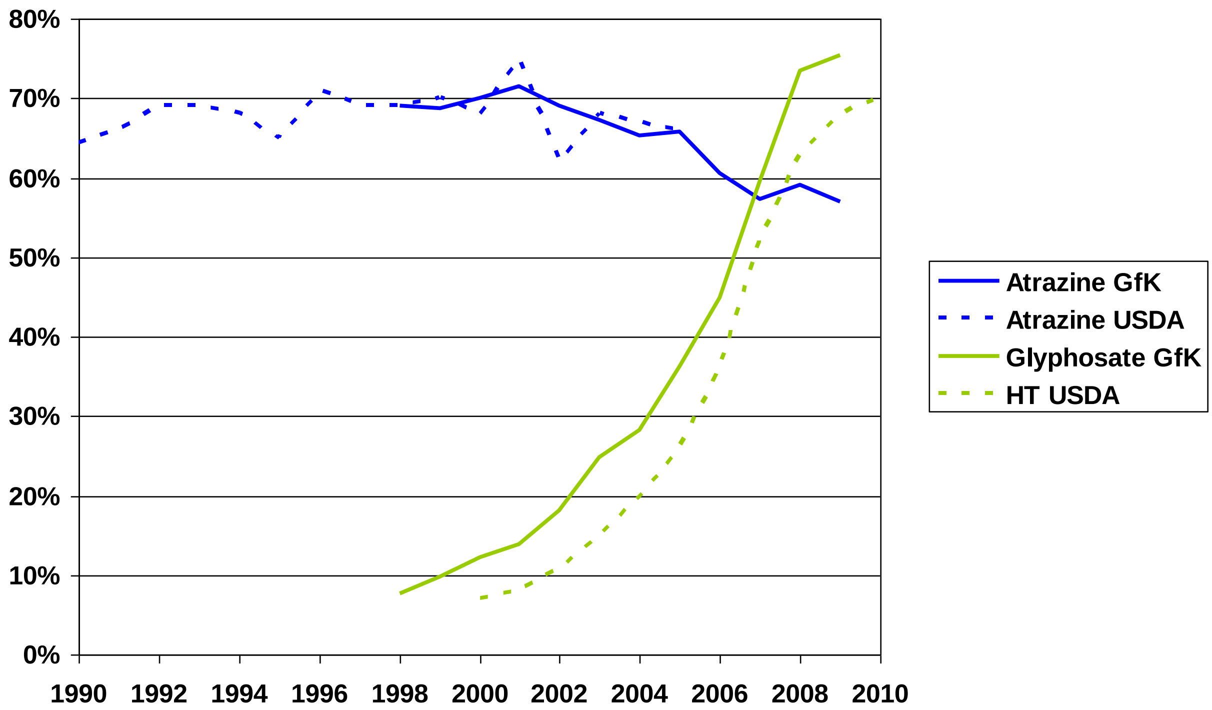

Figure 1. Percent of U.S. corn acres treated with atrazine, with glyphosate, and planted with an herbicide-tolerant (HT) variety (Sources: USDA-ERS 2011a; USDA-NASS 2010; GfK Kynetec 2010).

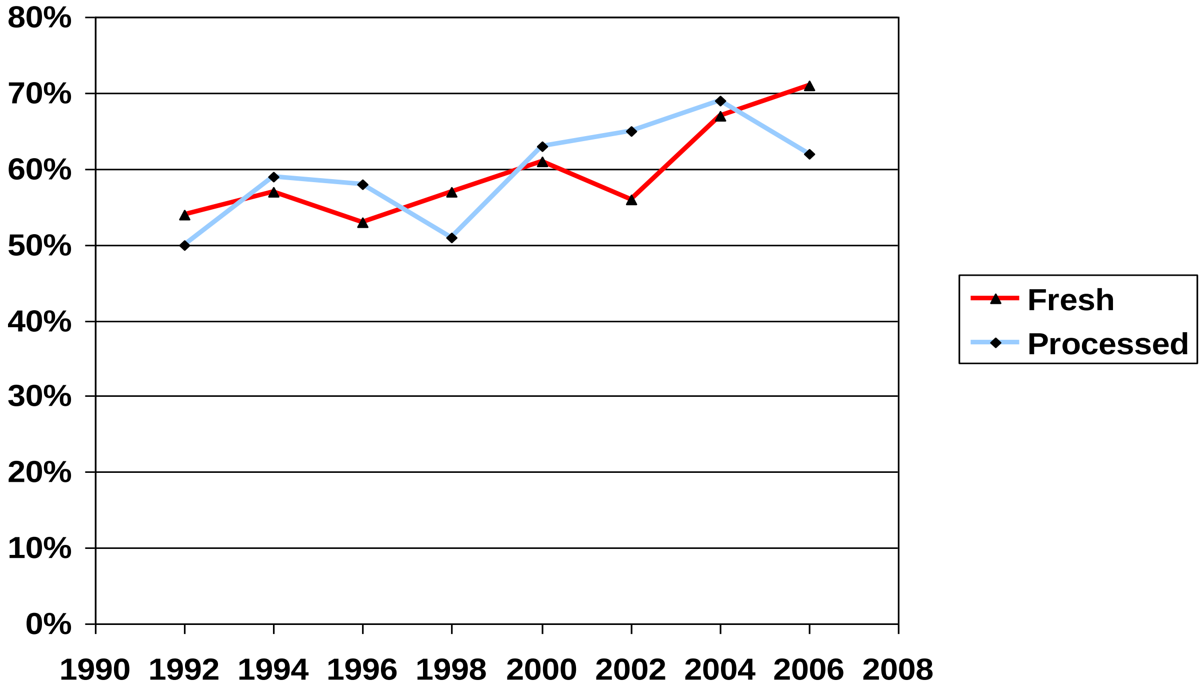

Figure 2. Percent of U.S. fresh and processed sweet corn planted acres treated with atrazine (Source: USDA-NASS 2010).

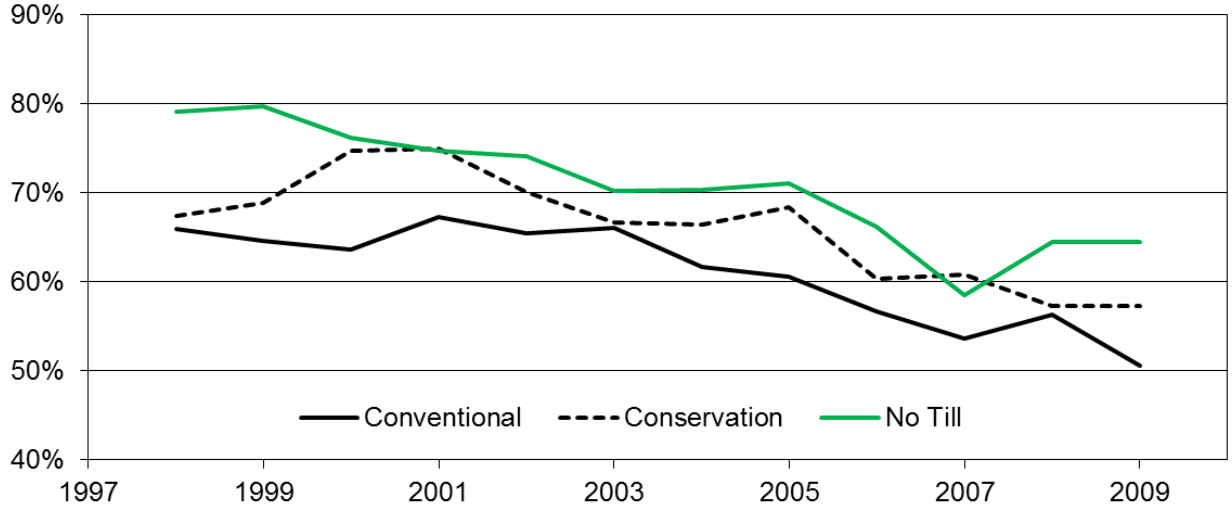

Figure 3. Percent of conventional tillage, conservation tillage and no-till corn acres treated with atrazine in the U.S. (Source: GfK Kynetec 2010).

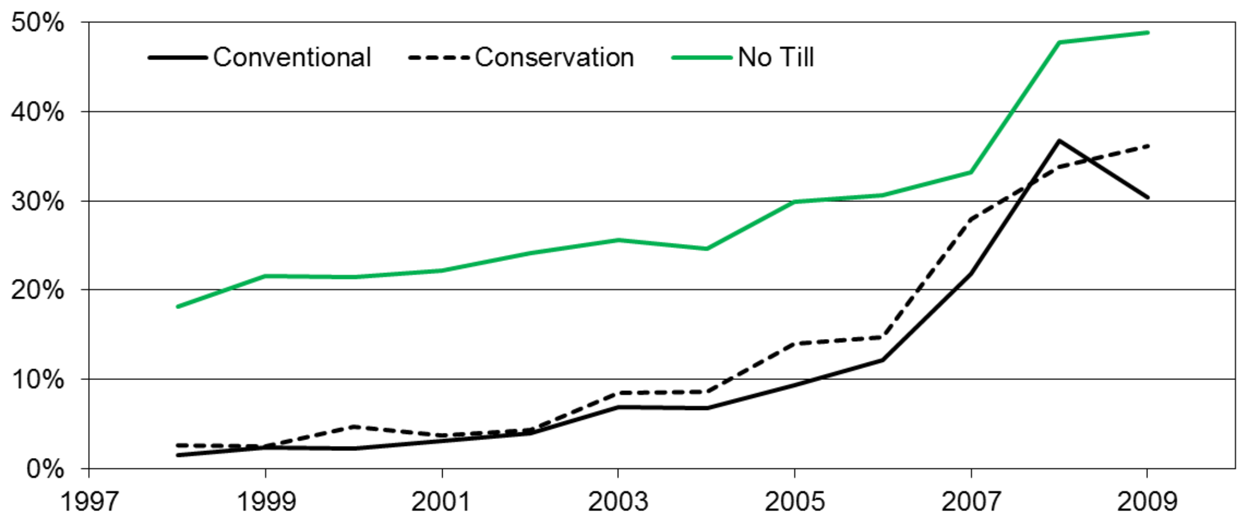

Figure 4. Percent of conventional tillage, conservation tillage, and no-till corn acres treated with both atrazine and glyphosate in the U.S. (Source: GfK Kynetec 2010).

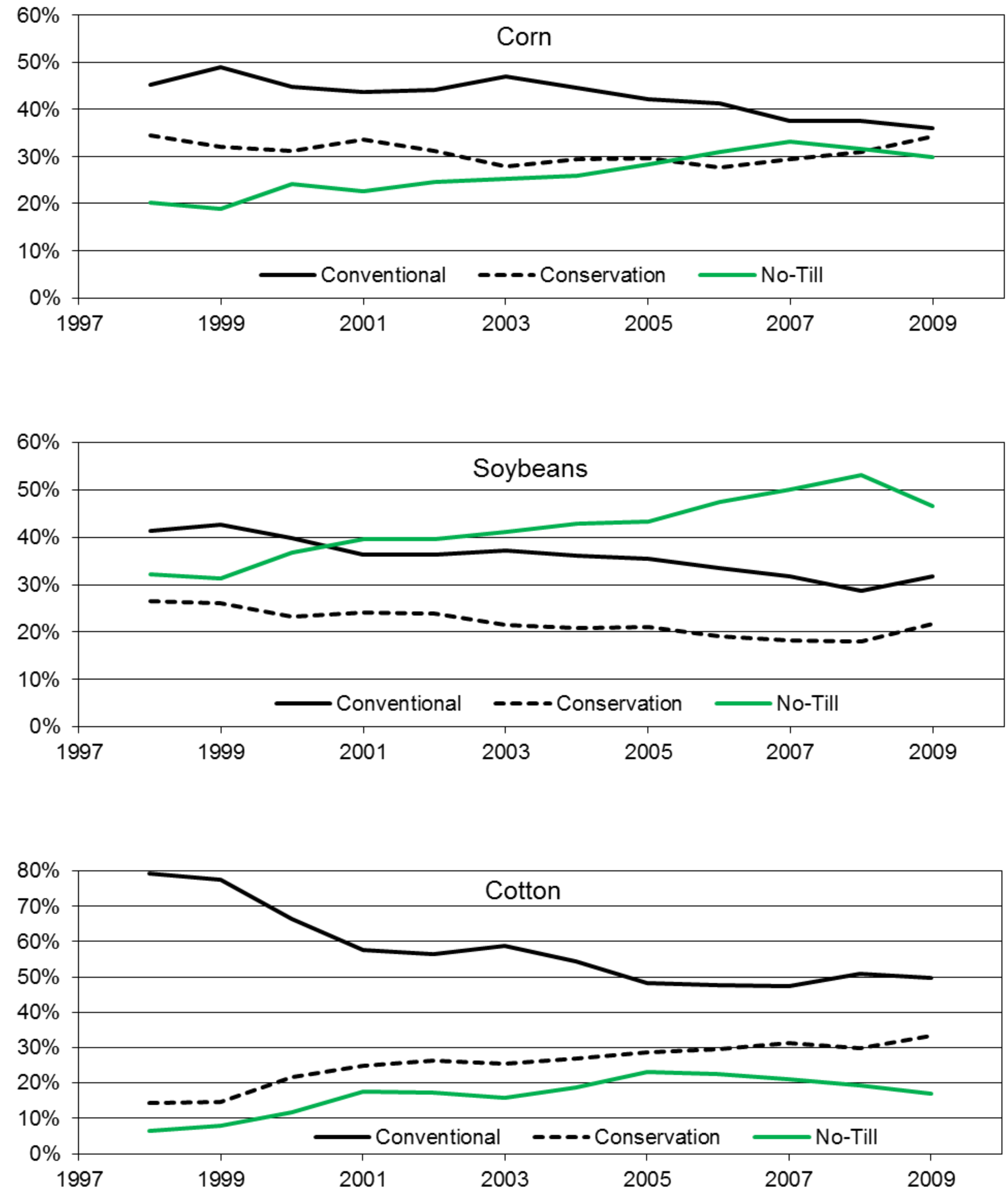

Figure 5. Percent of U.S. corn, soybean, and cotton acres planted using conventional tillage, conservation tillage and no-till (Source: GfK Kynetec 2010).

References

Abendroth JA, Martin AR and Roeth FW. 2006. Plant response to combinations of mesotrione and photosystem II inhibitors. *Weed Technol* 20:267-274.

Ackerman F. 2007. The Economics of Atrazine. *Int J Occup Env Heal* 13:441-449.

Bridges DC. 2008. Benefits of Triazine Herbicides in Corn and Sorghum Production, in *The Triazine Herbicides: 50 Years of Revolutionizing Agriculture*, ed. by LeBaron HM, McFarland JE and Burnside OC, Elsevier, Amsterdam, pp. 163-174.

Bridges DC. 2011. A Biological Analysis of the Use and Benefits of Chloro-*s*-Triazine Herbicides in U.S. Corn and Sorghum Production. Abraham Baldwin Agricultural College, Tifton GA. Online: http://www.abac.edu/president/.

Buhler DD. 1991. Early Preplant Atrazine and Metolachlor in Conservation Tillage Corn (*Zea mays*). *Weed Technol* 5:66-71.

Buhler DD. 1992. Population Dynamics and Control of Annual Weeds in Corn (*Zea mays*) as Influenced by Tillage Systems. *Weed Sci* 40:241-248.

Carlson G. 2008. The Use of Economic Benefit Models in Estimating the Value of Triazine Herbicides, in *The Triazine Herbicides: 50 Years of Revolutionizing Agriculture*, ed. by LeBaron HM, McFarland JE and Burnside OC, Elsevier, Amsterdam, pp. 153-162.

Claassen R, Breneman V, Bucholtz S, Cattaneo A, Johansson R and Morehart M. 2004. Environmental Compliance in U.S. Agricultural Policy: Past Performance and Future Potential. Agricultural Economic Report No. 832, USDA-ERS, Washington, DC. Online: http://www.ers.usda.gov/Publications/AER832/.

Davis VM, Gibson KD, Bauman TT, Weller SC and Johnson WG. 2009. Influence of Weed Management Practices and Crop Rotation on Glyphosate-Resistant Horseweed (*Conyza canadensis*) Population Dynamics and Crop Yield-Years III and IV. *Weed Sci* 57:417-426.

Elmore CL and Lange AH. 2008. Triazine Herbicides for Weed Control in Fruit and Nut Crops, in *The Triazine Herbicides: 50 Years of Revolutionizing Agriculture*, ed. by LeBaron HM, McFarland JE and Burnside OC, Elsevier, Amsterdam, pp. 211-224.

Esseks JD and Kraft SE. 1991. Land user attitudes toward implementation of conservation compliance farm plans. *J Soil Water Conserv* 46:365-370.

Fawcett RS. 2007. Triazine Herbicide Benefits in Reducing Erosion and Fuel Use in U.S. Corn Production. *Proceedings, Southern Weed Science Society* 60:205-208.

Fernandez-Cornejo J and Caswell M. 2006. The first decade of genetically engineered crops in the United States. Economic Information Bulletin Number 11, USDA-ERS, Washington, DC.

Ferrell JA and Witt WW. 2002. Comparison of Glyphosate with Other Herbicides for Weed Control in Corn (*Zea mays*): Efficacy and Economics. *Weed Technol* 16:701-706.

Foresman C and Glasgow L. 2008. US grower perceptions and experience with glyphosate-resistant weeds. *Pest Manag Sci* 64:388-391.

Frisvold GB, Boor A and Reeves JM. 2009. Simultaneous Diffusion of Herbicide Resistant Cotton and Conservation Tillage. *AgBioForum* 12:249-257.

Fuglie KO. 1999. Conservation Tillage and Pesticide Use in the Cornbelt. *Journal of Agricultural and Applied Economics* 31:133-147.

Fulton M and Keyowski L. 1999. The producer benefits of herbicide-resistant canola. *AgBioForum* 2:85-93.

Gebhardt MR, Daniel TC, Schweizer EE and Allmaras RR. 1985. Conservation Tillage. *Science* 230:625-630.

Gehlhar M, Winston A and Somwaru A. 2010. Effects of Increased Biofuels on the U.S. Economy in 2022. Economic Research Report No. 102, USDA-ERS, Washington, DC. Online: http://www.ers.usda.gov/publications/err102/.

GfK Kynetec. 2010. AgroTrak®. GfK Kynetec, St. Louis, MO.

Givens WA, Shaw DR, Kruger GR, Johnson WG, Weller SC, Young BG, Wilson RG, Owen MDK and Jordan D. 2009. Survey of Tillage Trends Following the Adoption of Glyphosate-Resistant Crops. *Weed Technol* 23:150-155.

Givens WA, Shaw DR Newman ME, Weller SC, Young BG, Wilson RG, Owen MDK, and Jordan DL. 2011. Benchmark study on glyphosate-resistant cropping systems in the United States. Part 3: Grower awareness, information sources, experiences, and management practices regarding glyphosate-resistant weeds. *Pest Manag Sci* 67:758-770.

Gorddard RJ, Pannell DJ and Hertzler G. 1995. An optimal control model for integrated weed management under herbicide resistance. *Aust J Agr Econ* 39:71-87.

Gorddard RJ, Pannell DJ and Hertzler G. 1996. Economic evaluation of strategies for management of herbicide resistance. *Agr Syst* 51:281-298.

Hager A. 2010. Corn and Soybean Herbicide Efficacy Tables. *The Bulletin*, March 26, 2010, University of Illinois Extension, Urbana-Champaign, IL. Online: http://bulletin.ipm.illinois.edu/article.php?id=1260.

Hager A. 2008. Multistate Ratings for Burndown Herbicide Efficacy. *The Bulletin*, April 18, 2008, University of Illinois Extension, Urbana-Champaign, IL. Online: http://bulletin.ipm.illinois.edu/article.php?id=904.

Hansen L and Ribaudo M. 2008. Economic Measures of Soil Conservation Benefits. Technical Bulletin Number 1922, USDA-ERS, Washington, DC. Online: http://www.ers.usda.gov/Publications/TB1922/TB1922.pdf.

Hawkins DE, Slife FW and Swanson ER. 1977. Economic Analysis of Herbicide Use in Various Crop Sequences. *Illinois Agricultural Economics* 17:8-13.

Heap IM. 2010. The International Survey of Herbicide Resistant Weeds, Corvallis, OR. Online: http://www.weedscience.org/.

Horowitz J, Ebel R and Ueda K. 2010. No-Till Farming is a Growing Practice. Economic Information Bulletin No. 70, USDA-ERS, Washington, DC. Online: http://www.ers.usda.gov/publications/eib70/.

Hurley TM, Mitchell PD and Frisvold GB. 2009a. Characteristics of Herbicides and Weed-Management Programs Most Important to Corn, Cotton, and Soybean Growers. *AgBioForum* 12:269-280.

Hurley TM, Mitchell PD and Frisvold GB. 2009b. Effects of Weed-Resistance Concerns and Resistance-Management Practices on the Value of Roundup Ready® Crops. *AgBioForum* 12:291-302.

Johnson WG, Bradley PR, Hart SE, Buesinger ML and Massey RE. 2000. Efficacy and Economics of Weed Management in Glyphosate-Resistant Corn (*Zea mays*). *Weed Technol* 14:57-65.

Johnson WG, Owen MDK, Kruger GR, Young BG, Shaw DR, Wilson RG, Wilcut JW, Jordan DL and Weller SC. 2009. U.S. Farmer Awareness of Glyphosate-Resistant Weeds and Resistance Management Strategies. *Weed Technol* 23:308-312.

Knowler D and Bradshaw B. 2007. Farmers' adoption of conservation agriculture: A review and synthesis of recent research. *Food Policy* 32:25-48.

Kroskinen WC and McWhorter CG. 1986. Weed Control in Conservation Tillage. *J Soil Water Conserv* 41:365-370.

Kruger GR, Johnson WG, Weller SC, Owen MDK, Shaw DR, Wilcut JW, Jordan DL, Wilson RG, Bernards ML and Young BG. 2009. U.S. Grower Views on Problematic

Weeds and Changes in Weed Pressure in Glyphosate-Resistant Corn, Cotton, and Soybean Cropping Systems. *Weed Technol* 23:162-166.

Larson JA, English BC, De La Torre Ugarte DG, Menard RJ, Hellwinkel CM and West TO. 2010. Economic and Environmental Impacts of the Corn Grain Ethanol Industry on the United States Agricultural Sector. *J Soil Water Conserv* 65:267-279.

LeBaron HM, McFarland JE and Burnside OC. 2008. The Triazine Herbicides: A Milestone in the Development of Weed Control Technology, in *The Triazine Herbicides: 50 Years of Revolutionizing Agriculture*, ed. by LeBaron HM, McFarland JE and Burnside OC, Elsevier, Amsterdam, pp. 1-12.

Marra MC and Piggott NE. 2006. 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, Springer, New York, pp. 145-178.

Marsh SP, Llewellyn RS and Powles SB. 2006. Social Costs of Herbicide Resistance: the Case of Resistance to Glyphosate. Poster Paper presented at the International Association of Agricultural Economists Conference, Gold Coast, Australia, August 12-18, 2006. Online: http://ageconsearch.umn.edu/bitstream/25413/1/pp060795.pdf.

Martin MA, Schreiber MM, Riepe JR and Bahr JR. 1991. The Economics of Alternative Tillage Systems, Crop Rotations, and Herbicide Use on Three Representative East-Central Corn Belt Farms. *Weed Sci* 39:299-307.

Mueller TC, Mitchell PD, Young BG and Culpepper AS. 2005. Proactive versus Reactive Management of Glyphosate-Resistant or Tolerant Weeds. *Weed Technol* 19:924-933.

Nolte SA and Young BG. 2002. Efficacy and Economic Return on Investment for Conventional and Herbicide-Resistant Corn (*Zea mays*). *Weed Technol* 16:371-378.

Orson JH. 1999. The Cost to the Farmer of Herbicide Resistance. *Weed Technol* 13:607-611.

Owen MDK. 2011. The Importance of Atrazine in the Integrated Management of Herbicide-Resistant Weeds. Working Paper, Iowa State University, Ames, IA. Online: http://www.weeds.iastate.edu.

Pannell D, Stewart V, Bennett A, Monjardino M, Schmidt C, Powles S. 2004. RIM: A Bioeconomic Model for Integrated Weed Management of *Lolium rigidum* in Western Australia. *Agr Syst* 79:305-325.

Pike DR, Knake EL and McGlamery MD. 2008. Weed Control Trends and Practices in North America, in *Triazine Herbicides: Risk Assessment,* ed. by Ballentine LG, McFarland JE and Hackett DS, ACS Symposium Series 683, American Chemical Society, Washington, DC.

Pike DR, Steffey K, Gray M, Kirby W, Edwards D and Hornbaker R. 1994. *Field Corn and Soybean Pesticide Use and Insecticide Cluster Assessment*. University of Illinois, Urbana, IL. (Cited in Carlson 2008).

Pimentel D, Acquay H, Biltonen M, Rice P, Silva M, Nelson J, Lipner V, Giordano S, Horowitz A and D'Amore M. 1992. Environmental and Economic Costs of Pesticide Use. *Bioscience* 42:750-760.

Pimentel D, Harvey C, Resosudarmo P, Sinclair K, Kurz D, McNair M, Crist S, Shpritz L, Fitton L, Saffouri R and Blair R. 1995. Environmental and Economic Costs of Soil Erosion and Conservation Benefits. *Science* 276:1117-1123.

Powles SB. 2008. Review: Evolved glyphosate-resistant weeds around the world: Lessons to be learnt. *Pest Manag Sci* 64:360-365.

Ribaudo MO and Bouzaher A. 1994. Atrazine: Environmental Characteristics and Economics of Management. USDA-Economic Research Service (USDA-ERS) *Agricultural Economic Report Number 699*, Washington, DC.

Scott BA and VanGessel MJ. 2007. Delaware soybean grower survey on glyphosate-resistant horseweed (*Conyza canadensis*). *Weed Technol* 21:270-274.

Singh M and Sharma SD. 2008. Benefits of Triazine Herbicides and Other Weed Control Technology in Citrus Management, in *The Triazine Herbicides: 50 Years of Revolutionizing Agriculture,* ed. by LeBaron HM, McFarland JE and Burnside OC, Elsevier, Amsterdam, pp. 199-210.

Smith DT, Richard EP and Santo LT. 2008. Weed Control in Sugarcane and the Role of Triazine Herbicides, in *The Triazine Herbicides: 50 Years of Revolutionizing Agriculture,* ed. by LeBaron HM, McFarland JE and Burnside OC, Elsevier, Amsterdam, pp. 185-198.

So YF, Williams II M M, Pataky JK and Davis AS. 2009. Principal canopy factors of sweet corn and relationships to competitive ability with wild proso millet (*Panicum miliaceum*). *Weed Sci* 57:296–303.

Sutton P, Richards C, Buren L and Glasgow L. 2002. Activity of mesotrione on resistant weeds in maize. *Pest Manag Sci* 58:981-984.

Swinton SM, Lybecker D and King R. 1994. The Effect of Local Triazine Restriction Policies on Recommended Weed Management in Corn. *Rev Agr Econ* 17:351-367.

Tegtmeier EM and Duffy MD. 2004. External Costs of Agricultural Production in the United States. *Int J Agric Sustain* 2:1-20.

Tracy WF. 2001. Sweet Corn, in *Specialty Corns*, ed. by Hallauer AR, CRC Press, Boca Raton, FL, 2nd ed., pp. 155–197.

US Department of Agriculture (USDA). 2011. *World Agricultural Supply and Demand Estimates*. USDA, Washington, DC. Online: http://www.usda.gov/oce/commodity/wasde/latest.pdf.

US Department of Agriculture-Economic Research Service (USDA-ERS). 2000. Farm Resource Regions. Agricultural Information Bulletin AIB-760. USDA-ERS, Washington, DC. Online: http://www.ers.usda.gov/publications/aib760/aib-760.pdf.

US Department of Agriculture-Economic Research Service (USDA-ERS). 2011a. Adoption of Genetically Engineered Crops in the U.S. USDA-ERS, Washington, DC. Online: http://www.ers.usda.gov/Data/BiotechCrops/.

US Department of Agriculture-Economic Research Service (USDA-ERS). 2011b. Commodity Costs and Returns: Data. USDA-ERS, Washington, DC. Online: http://www.ers.usda.gov/Data/CostsAndReturns/testpick.htm.

US Department of Agriculture-Economic Research Service (USDA-ERS). 2010a. Sugar and Sweeteners: Recommended Data. USDA-ERS, Washington, DC. Online: http://www.ers.usda.gov/Briefing/Sugar/Data.htm.

US Department of Agriculture-Economic Research Service (USDA-ERS). 2010b. U.S. Sweet Corn Statistics. USDA-ERS, Washington, DC. Online: http://usda.mannlib.cornell.edu/usda/ers/SweetCorn/.

US Department of Agriculture-National Agricultural Statistics Service (USDA-NASS). 2010. Agricultural Chemical Use Database. USDA-NASS, Washington, DC. Online: http://www.pestmanagement.info/nass/.

US Department of Agriculture-National Agricultural Statistics Service (USDA-NASS). 2011. Quick Stats: US & State – Crops: Online Database, Washington, DC. Online: http://www.nass.usda.gov/Data_and_Statistics/Quick_Stats_1.0/index.asp.

US Department of Agriculture-Natural Resource Conservation Service (USDA-NRCS). 2010. *2007 National Resources Inventory: Soil Erosion on Cropland*. USDA-NRCS, Washington, DC. Online: http://www.nrcs.usda.gov/technical/NRI/2007/2007_NRI_Soil_Erosion.pdf.

US Environmental Protection Agency (US EPA). 2002. *Assessment of Potential Mitigation Measures for Atrazine*, Biological and Economic Analysis Division, Office of Pesticide Programs, US Environmental Protection Agency, Washington, DC. Online: http://www.ppp.purdue.edu//ABA-02-03.pdf.

Ward C, Flanders A, Isengildina O and White F. 2002. Efficiency of alternative technologies and cultural practices for cotton in Georgia. *AgBioForum* 5:10-13.

Weersink A, Llewellyn RS and Pannell DJ. 2005. Economics of pre-emptive management to avoid weed resistance to glyphosate in Australia. *Crop Protection* 24:659-665.

West PC, Gibbs HK, Monfreda C, Wagner J, Barford CC, Carpenter SR and Foley JA. 2010. Trading carbon for food: Global comparison of carbon stocks vs. crop yields on agricultural land. *P Natl Acad Sci: Early Edition*. Online: www.pnas.org/cgi/doi/10.1073/pnas.1011078107.

Westcott P. 2007. Ethanol Expansion in the United States: How Will the Agricultural Sector Adjust? FDS-07D-01, USDA-ERS, Washington, DC. Online: http://www.ers.usda.gov/publications/fds/2007/05may/fds07d01/fds07d01.pdf.

Williams MM, Boerboom CM and Rabaey TL. 2010. Significance of Atrazine in Sweet Corn Weed Management Systems. *Weed Technol* 24:139-142.

Williams MM, Rabaey TL and Boerboom CM. 2008. Residual Weeds of Processing Sweet Corn in the North Central Region. *Weed Technol* 22:646-653.

Zollinger R, Christoffers M, Endres G, Gramig G, Howatt K, Jenks B, Lym R, Stachler J, Thostenson A and Valenti H. 2010. 2010 North Dakota Herbicide Compendium. *2010 North Dakota Weed Control Guide*, North Dakota State University Extension Service, Fargo ND, pp. 122-129. Online: http://www.ag.ndsu.edu/weeds/weed-control-guides/nd-weed-control-guide-1/wcg-files/18.1-Herb%20Comp.pdf.