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A biological analysis of the use and benefits of chloro-*s*-triazine herbicides in U.S. corn and sorghum production

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Executive Summary

A comprehensive simulation analysis of the use and benefits of chloro-*s*-triazine herbicides, in U.S. field corn, sweet corn and grain sorghum was conducted. This analysis employed methods used in previous assessments coupled with 2009 regionally-specific data on weed incidence by species, crop yield losses by weed species, herbicide efficacy by weed species and herbicide use data by active ingredient. The analysis also used the USDA Farm Resource Regions (FRRs) framework established in 2000 (USDA-ERS, 2000) as the aggregation basis for all analyses and reporting.

Results showed that across five USDA FRRs and two apportionment scenarios that, without availability of the triazine herbicides, the modeled weed control costs for U.S. field corn farmers would rise in seven out of 10 FRR by scenario analyses and yield would decline in all 10. The first scenario assumes that corn farmers would not have access to atrazine or simazine and that acres treated with these triazine herbicides would shift to other herbicides, including glyphosate, causing glyphosate use to expand beyond 2009 levels. In this scenario, field corn yield declines ranged from

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4.4 bushels to 15.3 bushels per current atrazine-treated acre. Averaged across all acres in the FRRs, yield declines ranged from 1.8 to 9.2 bushels per planted acre. Averaged across all U.S. field corn acres, the projected yield decline is 6.4 bushels per planted acre.

Since the prevalence of glyphosate-resistant weeds is increasing and because atrazine and glyphosate co-dominate the U.S. field corn herbicide market an unrestrained shift of current atrazine-treated acres to glyphosate may not occur. Therefore, the second scenario assumes that corn farmers would not have access to atrazine or simazine and that the glyphosate market share would remain constant at 2009 levels (approximately 75% of corn acres). In this scenario, field corn yields decline even more, between 5.7 bushels and 17.6 bushels per current atrazine-treated acre. Averaged across all acres in the FRRs, yield declines range from 2.9 to 13.6 bushels per planted acre. Averaged across all U.S. field corn acres, the projected yield decline is 7.7 bushels per planted acre. The difference between 6.4 and 7.7 bushels per planted acre predicts a 20% marginal yield loss due to maintaining the percent of field corn acres treated with glyphosate at 2009 levels, and thus causing the use of non-glyphosate and non-triazine alternatives.

Atrazine remains a keystone in the foundation of weed control programs for U.S. field corn farmers. It has been the most commonly applied herbicide in U.S. field corn for about 50 years. It remains the most common premix and tank-mix herbicide used today in U.S. corn production. Despite the phenomenal growth of the use of glyphosate in field corn, nearly 60% of all U.S. field corn acres are treated with atrazine. Approximately 50% of U.S. field corn that is treated with glyphosate is also treated with atrazine. An analysis of the potential value of field corn herbicides applied in sequence showed that atrazine was a component in 229 out of the 269 (85%) highest ranked three-way sequences.

Atrazine is equally important for grain sorghum farmers. In fact, fewer herbicides are registered for use in grain sorghum than in field corn. This analysis showed that if atrazine and propazine were not available to U.S. grain sorghum producers, grain sorghum yield would decline approximately 17 bushels per triazine treated acre, or 13 bushels per planted acre, nationwide. In addition, sweet corn yield also would decline without atrazine or simazine in all FRRs. Yield declines would range from 25% to 33% per atrazine-treated acre and approximately 20% per planted acre.

1. Background

1.1. __Use of triazine herbicides.__

The introduction of the triazine herbicides in the late 1950s revolutionized weed control in corn and grain sorghum, which is illustrated by the fact that by the mid-1960s atrazine achieved a dominant market share in the U.S. corn market and was of increasing importance to sorghum producers. The discovery, research, development and use of triazine herbicides in U.S. agricultural production are chronicled in detail in the book, *The Triazine Herbicides: 50 Years Revolutionizing Agriculture* (LeBaron, et al. 2008). Over the 50-plus years since its introduction, atrazine has been the most commonly used herbicide in U.S. agriculture. Bridges (2008) reported that because of its efficacy and spectrum of activity, reliability, safety to corn and sorghum, compatibility with other pesticides, flexibility in application, relative weather insensitivity and safety to applicators, atrazine became a keystone in the foundation of corn and sorghum weed control programs across the United States.

Because of its prominence in the market, finding new herbicides that could be used on a portion of the acres being treated with atrazine became a goal of many herbicide discovery programs. Many companies simply wanted to find a product that would complement atrazine. The often-stated objective of agricultural research scientists is to discover, develop and register products as efficacious as the triazines. This is a worthy goal, but one not yet accomplished. (Bridges, 2008).

1.2. Assessing the benefits of triazine herbicide use.

Quantitatively assessing the use and benefits of pesticides is an important and dynamic process. Because pesticides are registered, re-registered, and sometimes withdrawn and cancelled, the number of pesticides and how they may be used can change over time. New technology, crop production practices, farm programs, demands of the market and many other factors also contribute to the need to periodically update benefits assessments.

The last comprehensive, nationwide assessment of triazine herbicide use was conducted in 1995 through 1997 (Bridges, 1998; Carlson, 1998; Bridges, 2008; Carlson, 2008; Ciba Crop Protection, 1995 and 1996).

The methodologies used for previous benefits assessments varied. Some assessments were descriptive reviews, limited to showing pesticide use in terms of market share, applications rates and timing and the amount of pesticide used, without any estimation or measurement of the impact of pesticide use on crop yield and/or quality. Other assessments were opinion-based. This type of assessment typically relied on surveys to determine use of a pesticide and projections regarding potential yield and cost changes if that pesticide were not available. And, still other assessments have been robust, mechanistic and quantitative determinations of pesticide use and benefit, with substantial effort invested in projecting which alternative might be used and the resulting change in crop yield and weed control costs.

Many factors determine how an assessment is conducted:

1. The amount and complexity of herbicide use on a crop,
2. The size, value and importance of the crop,
3. The availability of reliable data on which to base the assessment, and
4. The level of robustness desired in the assessment outcome.

The methodology used for the aforementioned comprehensive triazine assessment conducted in 1995/1997 by Bridges and Carlson (Bridges, 1998; Carlson, 1998; Bridges, 2008; Carlson, 2008; Ciba Crop Protection, 1995) was bifurcated, and the robustness and rigor of the resultant analyses varied by crop depending on the aforementioned factors (Figure 1). One set of techniques was developed for triazine use in field corn, sweet corn, popcorn, and grain sorghum, and a second set of techniques was employed for the remaining minor uses or minor acreage (specialty) crops. Little yield information was available for minor uses and minor crops, so detailed analyses of crop yield response were not attempted.

The 1995/1997 assessment for corn and sorghum included both a qualitative component and a rigorous quantitative component. The qualitative assessment consisted of a thorough review of the label and associated product-specific information: performance profiles, including efficacy, spectrum, and crop tolerance; label comparisons; physical and chemical characteristics of the product; hazard profiles; economic benefits; and other relevant issues, such as use restrictions, etc. (Bridges, 1998; Bridges, 2008). The 1995/1997 analysis provided qualitative information about possible alternative or competitive herbicides and revealed some important deficiencies that would remain, should the triazines be unavailable for agricultural production.

The quantitative component of the 1995/1997 assessment (used for corn and sorghum) included the sequential use of two forms of mechanistic models that used research-based information on infestation by weed species, crop yield losses due to weeds by species, acres treated by herbicide treatment, historic and projected commodity prices and other related production and market information to estimate the benefits associated with use and the potential impact of a loss of one or more triazines from the marketplace (Taylor, 1993; Ciba Crop Protection, 1995; Bridges, 1998; Carlson, 1998; Bridges, 2008; Carlson, 2008). In the 1995/1997 assessment, 12 models were developed for the corn analysis and six for sorghum analysis (Figure 1).

2. Rationale for another assessment

Substantial change in corn production practices has occurred since the 1995/1997 assessment. For example, the introduction and swift adoption of the use of genetically-modified, glyphosate-tolerant field corn has significantly changed inputs in U.S. corn production (Figure 2). The number of pest resistance, crop quality and yield traits available to the farmer have dramatically increased. The fees and licensure requirements associated with many of these traits have changed decision-making processes and inputs. Herbicide resistant weeds are becoming more common and troublesome.

The remainder of this paper focuses on the background, methods and outcomes of a “behind-the-farm-gate assessment” of the use and benefits of triazine herbicides in the production of field corn, sweet corn and grain sorghum in the United States.

3. Methods

3.1. __Assumptions and guiding principles.__

The objective of this new assessment was to produce a comprehensive, rigorous and robust analysis of the use and benefits of triazine herbicides in U.S.-grown field corn, sweet corn and grain sorghum. Critical to achieving this goal, the following guiding principles were established:

- When available and appropriate, rely on data that are publicly available and/or subject to reference.
- Use (apply) data at one, or more, levels of aggregation higher than the point of collection to provide a stochastic nature to the results.
- Use transparent, mechanistic methods.
- Use pre-existing information to estimate required, but unavailable data. Conservative estimates are preferred, particularly when absolute measurements are absent and confidence intervals are large.
- Aggregation is preferred over disaggregation to the extent that it results in ranges.

3.2. __Assessment framework.__

The overall assessment framework is depicted in Figure 3. The approach has been used for previous assessments (Bridges, et al. 1990; Ciba Crop Protection, 1995 and 1996; Bridges, 1998; Carlson, 1998; Bridges, 2008; Carlson, 2008). The framework required detailed data in several critical areas to support the nine models that were used to produce regionally-specific yield and cost change estimates for field corn, sweet corn and grain sorghum across the United States. Table 1 summarizes the data requirements and sources for each of the models.

A common geographic framework was used for collecting data and reporting results. In 2000 the United State Department of Agriculture Economic Research Service announced the establishment of a reporting framework known as the USDA Farm Resource Regions (USDA-ERS, 2000). Hence, Farm Resource Regions (FRRs) were used as the analytical and reporting framework for this study, Figure 4. However, the FRRs used differed by crop, i.e. field corn, sweet corn and grain sorghum (Tables 2, 3 and 4, respectively).

3.3. Required data.

Efficacy. Data from 7,438 field research trials (65% university and 35% registrant) on weed control in corn were used to determine weed control values (efficacy) by species and herbicide treatment. For grain sorghum, data from 2,210 field research trials (74% university and 26% registrant) were used. Data definitions and criteria for inclusion were based on rates included on the label for each herbicide treatment included in models. Efficacy data included percent weed control by weed species for each of the herbicide treatments included in the models. The number of herbicide treatments varied by crop for field corn, sweet corn and grain sorghum (Tables 5, 6 and 7).

Percent acres treated and cost. Percent acres treated is defined as:

*Percent acres treated (%) = treatment acres/2009 USDA planted acres*100* and is reported for field corn, sweet corn and grain sorghum by FRR and by herbicide treatment (GfK Kynetec, 2009). Percent acres treated was used to calculate the protection value of each herbicide treatment in the 2009 market and to determine how growers might respond (apportionment) and to determine the change in cost and yield associated with alternative treatments if triazines were not available.

Weed incidence and potential damage. Weed incidence, or infestation level, is defined as the percent of crop acres (e.g. corn) that had a sufficient population of the specified weed, which if left uncontrolled would result in yield reduction. Potential damage was defined as the average percent yield loss expected to occur on infested acreage if the specified weed was left uncontrolled. This figure should be representative of an 'average loss condition,' not the 'worst case loss condition.'

Weed scientists at land-grant universities provided numerical information on weed infestation and associated yield loss. Data were collected and aggregated to the FRR by calculating the arithmetic mean of percent infestation and percent yield loss for the FRR. Zeroes were included in the arithmetic mean for infestation, as zero was a valid member of the set of possible answers regarding infestation and was accounted for in the mean and variance. However, when a respondent reported a zero for infestation for a particular weed, the percent yield loss value was automatically recorded as "missing" rather than zero, which would have biased the mean and variance. Data are shown in Table 8.

Target weed pests. Why and how herbicides are used by the farmer is important in understanding how possible alternatives may be chosen if previously-used herbicides were not available. In many former assessments the selection of a possible alternative and the estimation of the potential yield change is integrated into a single decision. Often a panel of experts is asked what alternative would likely be used and what will be the resulting yield change. Segregating these into separate data-driven decisions improves the understanding and reliability of the estimate. Identifying herbicide-specific and regionally-specific target weed species allows for a more mechanistic and consistent evaluation of possible alternatives.

An herbicide treatment may be used to control many weed species, but herbicide use is normally predicated for the control of a finite number of weeds. Therefore, to more precisely determine the intended target for which each herbicide treatment is currently used, five target weeds were identified for each herbicide, by FRR, based on FRR weed infestation and efficacy data.

Computational methods.

The required input data and computational framework is outlined in Figure 5. A common set of computational methods was applied to field corn, sweet corn and grain sorghum for all FRRs as defined in Tables 2, 3 and 4. USDA FRRs were used as the aggregation scale for regional effects.

Basic underlying calculations. The economic benefits associated with use of an herbicide treatment (or multi-herbicide treatment or premix treatment) were calculated using four different methods:

1. A substitution analysis,
2. A 1-way potential value analysis,
3. A 2-way potential value analysis, and
4. A 3-way potential value analysis.

A Fortran program was used for computational algorithms and decision steps which made possible the extraction of cost and yield changes. Protection value (PV) is the central benefits calculation. Protection value is the difference in crop value produced with and without the herbicide being examined (the targeted herbicide). Yield change can be computed from protection value.

To derive a benefit, two conditions must be met. Weeds against which the targeted herbicide has some degree of efficacy must be present at yield damaging levels, and the targeted herbicide must be applied properly to those areas. That those two factors coexist cannot usually be determined. Therefore, by assuming that infested acres occur randomly across the study region (FRR) and that the reported acres treated also occur randomly across the FRR, the minimum number of effectively treated acres would be the product of the fraction of percent area infested, the percent area treated, and the total planted acreage in the region. The maximum effectively-treated acres are equal to either the total acres infested with a weed, or the total acres treated with a target pesticide, whichever is smaller.

It is not reasonable to assume that farmers would spend money to randomly apply an herbicide with no idea of whether the controllable weeds are present. For example, if 100% of farmers said that they used the targeted herbicide to control weed species “A,” one could assume that weed species “A” was present on all treated acres. This would be a high degree of target specificity (100%). On the other hand, if only 10% of farmers said that they used it to control weed species “A”, then one could assume that much of the use occurred on land that was not infested with weed species “A”, a condition nearly the same as randomly applying the chemical for that weed. The degree of target specificity is multiplied by the difference between the minimum and maximum effectively treated acres and the product added to the minimum to get the effectively treated acres for each weed. Because individual target specificity values were not available and because previous work has shown that results are not usually compromised for weeds using upper mid-range values, target specificity was parametrically set at a value 75%.

In addition to degree of target specificity, target pests were identified for each herbicide and FRR based on infestation and efficacy data. While more weeds may be targeted by farmers, and certainly, most herbicides have efficacy against many weeds, herbicides are typically selected because they are effective against the weed species that are present in the field.

Historically, computations have clearly shown that there is a diminishing effect of each successive weed in a loss calculation sequence. In other words, percent crop yield loss is asymptotic and calculating yield losses on more than five moderate to serious weeds results in little additional damage. Thus, no more than five weeds were targeted for each herbicide. The targeting component of this assessment assured that pesticide replacement options were chosen because they had some degree of efficacy against the pests for which the target pesticide is actually being used.

The product of the percent acres infested and percent potential yield loss, sorted from largest to smallest, was used for ranking the weed species. The “independent” yield loss was this product. The value of the loss was the product of percent yield loss, the total acres in the market area, the expected or average yield of the crop and the price received. For “independent” losses, each weed was considered separately, as though no other weeds caused damage. The “decremental” yield loss was calculated in a two step process. First, yield losses were computed in a loop with the yield loss equal to the product of percent acres infested, potential yield loss, and remaining yield (initially equal to the average yield). Remaining yield was then the difference in the previous remaining yield minus the additional yield loss just calculated. After the loop was applied for all identified weeds, going in order of most serious to least, a maximum damage ratio was calculated if the just calculated damage exceeded the maximum damage reported for the crop and weed (an input parameter). The ratio was the maximum damage divided by the just calculated damage. The second step repeated the first loop, but the yield loss for each step was reduced by the maximum damage ratio.

Net return to treatment (NRT) is the protection value (PV) less total treatment cost per acre. NRT more closely approximates the actual net return from an herbicide treatment than the PV since it subtracts application and material costs of the pesticide. Return ratio is the third economic measure which was computed for each herbicide.

<u>Substitution analysis – 1-way using 2009 percent acres treated</u>. This analytical method was used as the primary method to estimate possible yield and cost changes associated with the possible loss of triazine herbicides. It sequentially uses the basic underlying computational methods that were described previously to calculate the protection value for each herbicide treatment (32 for field corn, 17 for grain sorghum and 16 for sweet corn) and using the national commodity price per bushel and for each FRR, using average yield and percent acres treated by herbicide treatment, potential infestation and damage, efficacy of the herbicide against its target weeds, target weed,

and specificity of use in the FRR. Therefore, the economic benefit is computed based on the current herbicide use in the FRR, reflecting infestation and damage characteristics in the FRR.

Apportionment scenarios and calculations using the Substitution analysis – 1-way using 2009 percent acres treated. The comparative protection value was determined by ranking in descending order by protection value all non-triazine alternative herbicide treatments from partial budgeting procedure described above. Apportionment scenarios varied by crop (described later in the results section). However, in all apportionment processes, acres treated by the targeted herbicide treatment were apportioned proportionally to the percent acres treated with relevant alternative herbicide treatments. This process produces aggregate cost and yield change values that reflect current percent acres treated for possible “alternative” herbicide treatments. Aggregate cost and yield changes reflect most likely, one-on-one replacement of the target herbicide treatment since the protection values are calculated using the target weeds for the target herbicide. The model reapportions acres to a set of single herbicide treatments (the treatment may include more than one active ingredient) and calculates the cost and yield differentials. The costs of additional passes across the field that may result from the reapportionment were not included in the herbicide costs. This analysis gives yield and cost changes by FRR for a mix of currently-used “alternative” treatments.

Potential value – 1-way analysis. The previous analysis (Substitution analysis – 1-way using 2009 percent acres treated) considers how herbicide treatments are currently used in the FRR. The “Potential Value” analysis uses the same underlying calculation methods, but it does not consider how herbicide treatments are currently used in the market. Rather, it takes each herbicide treatment and sequentially and independently calculates potential protection value if the herbicide treatment was used on all crop (i.e. field corn) acres in the FRR, and it considers all weed species listed in the input data set. In other words, it treats the FRR as one large field in which all of the weed species listed for that FRR occur in the field proportional to infestation level.

While the assumption that one, and only one, herbicide treatment would be used across the FRR is illogical from an operational standpoint, it is very important conceptually in that a protection value calculated in this manner reflects the potential economic benefit of the herbicide treatment across the entire FRR. This analysis provides powerful information about the herbicide treatment because it integrates efficacy across all weed species and infestation and potential damage if weeds are not controlled. Absolute protection values derived from this analysis is of secondary, if any, value. What is important is that it provides a powerful means of comparing the relative value of herbicide treatments within the FRR.

Potential value – 2-way analysis. This analysis is similar to the previously described “Potential value – 1-way analysis” except that it produces a potential protection value calculation for all permutations of herbicide treatments taken two at a time. So, it provides information on protection value in the FRR assuming that two, and only two, treatments are used on every acre in the FRR. Premixed, tank-mixed and sequential herbicide treatments are common practice. This analysis simply provides quantitative information about the potential value of such combinations. For two-way combinations a composite efficacy table was created where each combined efficacy was the product of the two individual efficacies. Costs of materials and applications are the sums of the individual treatments.

Potential value – 3-way analysis. This analysis is similar to the previously described potential value analyses except that it produces a potential protection value calculation for all permutations of herbicide treatments taken three at a time.

Regional cost and yield changes were estimated using nine regional models: five for field corn, three for sweet corn and one for grain sorghum. Additional details relative to this part of the analysis have been published previously (Ciba Crop Protection, 1995 and 1996; Bridges, 1998).

4. Results and Discussion

4.1. Field corn – substitution analysis using current market shares with two apportionment scenarios.

Atrazine remains an important tool for U.S. field corn producers. In fact, it is an integral component of the weed control program for more than one half of U.S. corn growers. Farmers used 44 herbicide active ingredients to control weeds in U.S. field corn during 2009 (Gfk Kynetec, 2009), yet atrazine was used on nearly 60% of U.S. corn acres during 2009 (Figure 2). Atrazine is used for weed control in field corn in many different ways: preemergence, post-emergence, alone, in commercial premixes, in field tank mixes and in sequences with other herbicides. In fact, for all but three of the 44 herbicides, atrazine was a tank-mix or pre-mix partner more than 25% of the time in U.S. field corn (Figure 6). For 33, or 75% of the 44 herbicide active ingredients, atrazine was a partner 50%, or more, of the time. And, for 18, or 41%, of the herbicides, they were applied 75%, or more, of the time with atrazine. So, determining the total value of atrazine for weed control in field corn is complex. Determining how and when other herbicides might be used as an alternative to a specific atrazine use if atrazine were not available is an even more complicated challenge.

Non-triazine herbicide scenarios. Determining the potential impact of the loss of atrazine for U.S. corn growers hinges on the ability to predict behavioral responses by farmers, which will in turn dictate the redistribution/reallocation of current atrazine-treated acres. An *a priori* construct is that in the short term (immediate, next year after a change) farmers will use currently-available alternative product(s). The set of alternative products will be the current set of herbicides minus atrazine and will not include new products. Apportionment of current atrazine acres occur under two scenarios.

The “non-triazine use” scenarios included not using atrazine and simazine in field corn and sweet corn and not using atrazine and propazine in grain sorghum. For field corn, two “non-triazine” scenarios were defined. One scenario, Non-triazine – Increasing glyphosate acres, assumes percent glyphosate-treated field corn acres increase. The second scenario, Non-triazine – 2009 glyphosate acres, assumes that the percent of field corn acres treated with glyphosate remains at 2009 levels.

Scenario 1 – Non-triazine – increasing glyphosate acres. This scenario is based on the fact that glyphosate is a co-dominant herbicide, along with atrazine, in U.S. corn production (Figure 2). Since the introduction of genetically-modified, glyphosate-tolerant corn in the late 1990s, farmers have become steadily and increasingly reliant on the use of glyphosate for weed control in corn (Figure 2). The percent acres treated with atrazine declined slightly during these years, but the fact is that atrazine is still used on nearly 60% of the total U.S. field corn acreage. Moreover, approximately one half (32 million) of the 64 million acres of field corn in the U.S. that are treated with glyphosate is also treated with atrazine. These facts demonstrate the importance of continued reliance on atrazine in this cropping system.

This scenario is also based on a principle that when a pesticide is not available in the market, farmers will shift to a set of existing possible alternative products in a way that is proportional to the use of the alternative prior to loss of the dominant product. Because glyphosate co-dominates the U.S. corn herbicide market along with atrazine, it is logical to conclude that a significant portion of the atrazine acres might shift to glyphosate if atrazine were not available. Therefore, under this scenario current atrazine acreage was apportioned among existing biologically-relevant products in accordance with their current (2009) use in the market. Because glyphosate is already so prominent in the marketplace, a substantial portion of atrazine acres were apportioned to glyphosate under this scenario. The apportionment process under Scenario 1 often shifted formerly-atrazine acres to glyphosate, resulting in glyphosate being applied to 100% of the corn acres in four of five field corn FRRs. The exception was the Northern Crescent, where glyphosate use increased to 93% of the corn acres.

Scenario 2 – Non-triazine – 2009 glyphosate acres*.* The aforementioned shift of many atrazine acres to glyphosate-treated acres would be likely to occur in a non-triazine scenario except for two important factors,

1. A large percentage of corn acres are already treated with glyphosate (about 75% nationally) and

2. The percentage of corn acres on which glyphosate-resistant weeds are problematic is increasing.

Either, or both, of these factors will tend to dampen a shift towards more glyphosate. Furthermore, whether or not farmers continue to use glyphosate once glyphosate-resistant weeds are prevalent, it will be necessary to include other herbicides to control the weeds formerly controlled by atrazine and/or glyphosate. For these reasons, in this scenario, current atrazine acres are apportioned to existing and biologically-relevant non-glyphosate products in accordance with their current use (2009 use data) in the market, resulting in no additional corn acres treated with glyphosate.

<u>Cost, yield, and net return changes for corn if atrazine and simazine were not available</u>. *Scenario 1* – Non-triazine – Increasing glyphosate acres*.* Substitution analyses revealed that under Scenario 1, weed control costs for corn producers would increase in all five USDA Farm Resource Regions (FRR) without atrazine (Table 9). More importantly, field corn yield would decline in all FRRs. Yield declines ranged from 4.4 to 15.3 bushels per atrazine-treated acre and 1.8 to 9.2 bushels per planted acre (Table 9). The weighted U.S. average yield decline was 6.4 bushels per planted acre. Across FRRs, net returns to corn farmers declined by $12.99 to $53.07 per atrazine-treated acre and $7.71 to $37.14 per planted acre, with corn prices at $3.75 per bushel. The total U.S. farm gate loss (to field corn farmers) under Scenario 1 was estimated to be $2.5 billion annually.

Scenario 2 – Non-triazine – 2009 glyphosate acres*.* Substitution analyses revealed that under Scenario 2 weed control costs for corn producers would increase in 2 FRRs without atrazine (Table 10). More importantly field corn yield would decline in

all FRRs. Yield declines ranged from 5.7 to 17.6 bushels per atrazine-treated acre and 2.9 to 13.6 bushels per planted acre (Table 10). The weighted U.S. average yield decline was 7.7 bushels per planted acre. Net returns to corn farmers declined from $20.20 to $65.82 per atrazine-treated acre and $11.30 to $50.84 per planted acre, at a corn price of $3.75 per bushel. The total U.S. farm gate loss (to field corn farmers) under Scenario 2 was estimated to be $2.9 billion annually. These data indicate that the potential economic impact of a possible loss of atrazine to U.S. corn farmers is large under any circumstance, but the uncertainty associated with increasing glyphosate-resistant weeds makes the impact larger than these estimates. No doubt farmers would face greater expense and less weed control, hence lower yields, if atrazine and simazine were not available and glyphosate resistance continued to increase. The cost and yield impact to current simazine users was not included in the analysis.

4.2. Field corn, potential value – 1-way analysis.

Because of the similarity of results across FRRs, data are presented only for the Heartland FRR for Field Corn. The Heartland FRR includes more than 57% of all U.S. field corn acres. Under this analysis protocol, for the 32 treatments, atrazine was included in four of the 10 treatments with the greatest protection value. For the purpose of presentation, treatments were grouped as follows: 1) treatments that included atrazine, n=6; 2) treatments that included glyphosate, n=3; and, 3) treatments that included neither atrazine nor glyphosate, n=23. The arithmetic mean protection value was calculated for each of these groups and the mean of the “atrazine” group was used as the standard. Doing so, the “glyphosate” group produced a protection value 3.5% higher than the “atrazine” group and the “neither” group produced a protection value

19.3% lower than the “atrazine” group. The grand mean for all non-atrazine-containing treatments was 13.3% less than for the “atrazine” group. This illustrates the importance of atrazine to Heartland field corn farmers. These results indicate that if atrazine were not available at a time when the efficacy of glyphosate is being challenged by the increasing prevalence of glyphosate-resistant weeds would likely result in a significant decline in weed control and an associated decline in corn yields.

4.3. Field corn, potential value – 2-way analysis.

For the reasons stated above, data are presented only for the Heartland FRR, which includes more than 57% of the U.S. field corn acreage. For the purpose of presentation, 2-way treatments were sorted from highest to lowest protection value. Results were summarized for the 269 combinations having the highest protection value. Combinations were grouped as follows 1) treatments that included atrazine or simazine, n=143, 2) treatments that included glyphosate, n=85, 3) treatments that included neither atrazine/simazine nor glyphosate, n=41.

The arithmetic mean protection value was calculated for each of these groups and the mean of the “atrazine” group was used as the standard. Doing so, the “glyphosate” group produced a protection value 2.2% higher than the “atrazine” group and the “neither” group produced a protection value 2.0% lower than the “atrazine” group. It is noteworthy that 143, or 53%, of the 269 highest ranked combinations included atrazine and/or simazine (Figure 7). These results further illustrate the importance of atrazine, in that even when sequences of the best “non-glyphosate alternatives” treatments are used, yields declined.

4.4. Field corn, potential value – 3-way analysis.

Again, for the reasons stated above, data are presented only for the Heartland FRR, which includes more than 57% of the U.S. field corn acreage. With the best 3-way treatments across all Heartland FRR acres, estimating yield differences became very difficult. The data clearly substantiate the importance of atrazine in weed control programs for Heartland FRR corn farmers in that atrazine was used in 229, 84 and 21 first, second and third sequence treatments out of the 269 highest rated 3-way sequences (Figure 8). This equates to 85, 31, and 8 percent of the sequences, respectively. While these sequences are not absolutely linked to time of application in the sequence, the data clearly demonstrate the importance of atrazine for residual weed control since it occurred in 85% of the first sequences.

4.5. Sweet corn – substitution analysis using current market shares with one apportionment scenario.

Similar to field corn, atrazine remains an extremely important part of the weed control program in sweet corn. In fact, one can make the case that atrazine is relatively more important to sweet corn farmers than it is to field corn farmers because several herbicides that are registered for use in field corn are not registered for use in sweet corn (Table 7). More importantly, to date, there are no commercially-available glyphosate-tolerant sweet corn varieties or hybrids. Furthermore, sweet corn is less tolerant of some herbicides than is field corn, which further restricts options to the sweet corn farmer.

Scenario 1 – No Atrazine/Simazine. Substitution analysis revealed that under Scenario 1 aggregate weed control costs for sweet corn producers would increase in two of the three FRRs without atrazine (Table 11). More importantly, sweet corn yield would decline in all Farm Resource Regions. Yield declines ranged from 25% to 33% per atrazine-treated acre. Yield decline was approximately 20% per planted acre for all FRRs.

4.6. Grain sorghum – substitution analysis using current market shares with one apportionment scenario.

Similar to field corn and sweet corn, atrazine remains an extremely important part of the weed control program in grain sorghum. Grain sorghum farmers have fewer options (17) than field corn (32) farmers, and eight of the 17 sorghum options contained atrazine or propazine. There is no doubt that without the availability of atrazine or propazine, grain sorghum farmers would lose important components of their residual weed control programs. Therefore, an assessment of the potential impact to these farmers is absolutely critical to estimating the potential impact of the loss of triazine herbicides to U.S. agriculture. Table 6 shows how few alternatives are available to the grain sorghum farmer.

Because glyphosate is not available for use in grain sorghum, only one scenario was considered in the analysis for grain sorghum, production without atrazine or propazine. Substitution analyses to a set of single alternative treatments revealed that the modeled weed control costs for grain sorghum producers would decrease since there are few options for weed control in the absence of atrazine and propazine (Table 12). More importantly, grain sorghum yield would decline substantially for U.S. grain sorghum producers. Yields are predicted to decline by 17.7 bushels per triazine-treated acre and 13.1 bushels per planted acre (Table 12). Net returns to grain sorghum farmers declined by $57.99 per triazine-treated acre and $42.91 per planted acre, using a price of $3.50 per bushel. The total U.S. farm gate loss to grain sorghum farmers was estimated to be $296 million.

5. Summary of Findings - Impacts

Comparative analyses and computer simulations revealed no true replacement(s) for triazine herbicides. Unlike the 1995/1997 analysis by the author, nonchemical alternatives were not included in the 2011 analysis. The logistics and costs associated with hand weeding or cultivation of more than 86 million acres of U.S. field corn, 584 thousand acres of sweet corn and 6.9 million acres of grain sorghum are impractical and the environmental costs of cultivation are great. Multiple cultivation passes would nullify the tremendous benefits of conservation tillage. Reversing the long-term trend for increasing the percent of U.S. cropland acres in conservation tillage practices is undesirable. It will lead to increased soil erosion, surface water runoff, sediment levels in water and increased on-farm petroleum use.

Former analyses included many of the alternative herbicides included in this analysis (Bridges, 1998; Bridges, 2008). The 1995/97 qualitative assessment component revealed strengths and weaknesses for individual possible alternative herbicides. As a part of this current assessment, information from the former assessment was reviewed, revised and updated to include new alternatives registered since the former assessment.

Relative to atrazine use in field corn, sweet corn and grain sorghum, the following characteristics were identified as effectively irreplaceable benefits associated with atrazine use:

Application flexibility. Residual control of weeds is obtained with either preemergence or postemergence applications of atrazine. Atrazine can be applied during the fallow season, early preplant, immediately prior to or after corn planting, or postemergence. It can be used preemergence or postemergence in many sorghum producing areas, with postemergence application being a great benefit where edaphic and climatic conditions do not permit preemergence application.

Premix and tank-mix compatibility. Atrazine mixes well with many herbicides. Compatibility and antagonism problems are rare. In fact, its premix compatibility is so good that atrazine is used more often than any other herbicide as a premix component in corn herbicide products. Furthermore, because of the tremendous margin of corn safety, mixes do not typically pose a risk for increased crop injury. Atrazine remains a keystone in corn weed control in the U.S. For (33, or 75%, of the 44 herbicide active ingredients used in field corn in the U.S. in 2009, atrazine was applied in mixture 50%, or more, of the time (Figure 6). For 18 of the herbicide active ingredients used, 75%, or more, of their base acres include atrazine (Table 13).

Crop tolerance. The margin of crop tolerance to atrazine is excellent in field corn, sweet corn and grain sorghum. Corn injury does not occur, even with use at maximum labeled rates. Postemergence tolerance to atrazine in corn is so exceptional that it can be used with a variety of carrier and/or adjuvant systems to enhance herbicidal activity on target weeds. Grain sorghum tolerance is good, and when applied according to label directions, grain sorghum injury is rare.

Weather insensitivity. Atrazine efficacy is relatively unaffected by weather. Since it is not particularly susceptible to photodegradation or to volatility, it can be applied under a variety of conditions and still be expected to deliver weed control benefits when rain occurs. The mode of action of atrazine in higher plants is such that sensitivity of susceptible plants is only minimally affected by environmentally-induced changes in plant growth, unlike many alternative herbicides that are efficacious only on rapidly growing plants.

Broad-spectrum weed control. Atrazine and simazine control a broad spectrum of broadleaf and grass weeds. In fact, of the 31 weeds species considered in the analysis, atrazine provides a higher level of control of a greater number of those species than any other herbicide, except glyphosate which does not provide residual control.

Tillage compatibility. Because atrazine provides both postemergence and residual preemergence weed control, it fits well into conventional, conservation and no-till production systems. Research indicates that dependency on atrazine increases when tillage is reduced, and in fact, currently available data indicate that 50.5%, 57.2% and 64.5% of conventional, conservation, and no-till field corn acreage, respectively, is treated with atrazine (GfK Kynetec, 2009).

Economical weed control. Atrazine provides very cost-effective weed control. The herbicide provides broad spectrum residual control and minimizes follow-up treatments, making net return to treatment costs very good.

Worker and environmental safety. Atrazine and simazine are safe to apply according to directions on the label. Nontarget safety margins are good because atrazine is nonvolatile and has low specific activity. In addition, avian, mammalian, and aquatic toxicities are low. Relative safety to nontarget plant species is a positive characteristic that is not always found in alternative products.

Resistance management. While it is true that triazine-resistant weeds have been known to exist since the 1970s, the practical or economic importance of triazine-resistant weeds has not proved to be as great as some predicted. Triazine resistance is different than the resistance developed to most herbicides because it is intimately connected with a lack of fitness or vigor due to a photosynthetic deficiency in the resistant weed (LeBaron, 2008). The triazine herbicides are essential to managing weed populations that are resistant to herbicides with other modes of action. In cropping systems where soybeans and corn are in rotation, the triazines provide important opportunities to rotate modes of action away from glyphosate and ALS-inhibitor herbicides for which the incidence of resistant weed populations are on the rise.

Table 1. Summary of data requirements for 2011 analysis of use and benefits of triazine herbicides in U.S. corn, sweet corn and grain sorghum production.

Data type	Source(s)
Efficacy data – percent weed control by weed species (31) and herbicide treatments (32 for field corn; 16 for sweet corn; 17 for grain sorghum)	Database of field research trials, which includes trials conducted by public sector cooperators, contractors and registrant scientists. Trial numbers: corn=7,438 and grain sorghum=2,210.
Current use (2009 percent treated acres) and cost – use data by herbicide treatment, by FRR; average production costs by FRR	GfK Kynetec and E-Z Trak.
Weed incidence and potential damage – by weed species (31), by FRR	2010 survey of university weed science professionals from around the United States; comparative analysis to sources used in previously-reported studies.
Target weed species by herbicide treatment, FRR and crop.	Computed from efficacy, infestation and loss data by crop and FRR
2009 crop year planted acres by FRR	United States Department of Agriculture
2009 crop year average yields by FRR	United States Department of Agriculture
2009 crop year average variable cost of production by FRR	United States Department of Agriculture

Table 2. Acreage, yield, variable production costs and aggregation scenario for field corn by FRR.

USDA Farm Resource Region[1]	2009 USDA Planted Acreage	Cumulative Acreage	Cumulative % of U.S. acres	Variable cost of production ($/acre)	2009 Yield (bu/acr
Heartland	49,313,200	49,313,200	57.22	305	1
Northern Crescent	11,017,500	60,330,700	70.01	324	1
Northern Great Plains	6,183,700	66,514,400	77.18	258	1
Prairie Gateway	11,783,600	78,298,000	90.86	358	1
Southern Seaboard	2,741,100	81,039,100	94.04		
Mississippi Portal	2,155,300	83,194,400	96.54		
Eastern Uplands	1,279,800	84,474,200	98.02		
Fruitful Rim	1,587,300	86,061,500	99.86		
Basin and Range	117,500	86,179,000	100.00		
Total	**86,179,000**				
Rest of Nation	**7,881,000**		**9.14**	**315**	**1**

[1] Farm Resource Regions highlighted with grey background were combined to form a single "FRR" called Rest of Nation.

Table 3. Acreage, variable production costs and aggregation scenario for sweet corn by FRR.

USDA Farm Resource Region[1]	2009 Planted Acreage	Cumulative Acreage	Cumulative % of U.S. acres	Variable cost of production ($/acre)
Heartland	106,293	106,293	18.21	Varies by type of production, fresh market versus processing.
Northern Crescent	241,012	347,305	59.50	
Northern Great Plains		347,305	59.50	
Prairie Gateway		347,305	59.50	
Southern Seaboard	26,000	373,305	63.95	
Mississippi Portal		373,305	63.95	
Eastern Uplands	13,301	386,606	66.23	
Fruitful Rim	189,308	575,914	98.67	
Basin and Range	7,792	583,706	100.00	
Total	583,706			
Rest of Nation	47,093			

[1] Farm Resource Regions highlighted in grey background were combined to form a single "FRR" call Rest of Nation.

Table 4. Acreage, yield, variable production costs and aggregation scenario for grain sorghum by FRR

USDA Farm Resource Region	2009 Planted Acreage	Cumulative Acreage	Cumulative % of U.S. acres	Variable cost of production ($/acre)	2009 Yield (bu/acre)
Heartland	159,932	159,932	2.32		
Northern Crescent		159,932	2.32		
Northern Great Plains	185,509	345,441	5.01		
Prairie Gateway	5,526,577	5,872,018	85.23	159	64
Southern Seaboard	60,583	5,932,601	86.10		
Mississippi Portal	137,079	6,069,680	88.09		
Eastern Uplands	45,340	6,115,020	88.75		
Fruitful Rim	774,987	6,890,007	100.00		
Basin and Range		6,890,007	100.00		
Total	6,890,007				
Rest of Nation	1,363,430			159	64

[1] *Farm Resource Regions highlighted with grey background were combined to form a single "FRR" called Rest of Nation.*

Table 5. List of herbicide treatments used in the 2011 analysis, field corn.

Herbicide treatment	Time of Application	Herbicide treatment	Time of Application
Atrazine	Before Emergence	Glyphosate	After Emergence
Acetochlor + atrazine	Before Emergence	2,4-D	After Emergence
S-metolachlor + mesotrione + atrazine	Before Emergence	Mesotrione	After Emergence
S-metolachlor + atrazine	Before Emergence	Dicamba + diflufenzopyr	After Emergence
Acetochlor	Before Emergence	Glufosinate	After Emergence
Isoxaflutole	Before Emergence	Dicamba	After Emergence
Atrazine + dimethenamid-P	Before Emergence	Tembotrione + safener	After Emergence
Simazine	Before Emergence	S-metolachlor + glyphosate + mesotrione	After Emergence
S-metolachlor	Before Emergence	Clopyralid + flumetsulam	After Emergence
Pendimethalin	Before Emergence	Rimsulfuron + thifensulfuron	After Emergence
Flufenacet + isoxaflutole	Before Emergence	Topramezone	After Emergence
Dimethenamid, -P	Before Emergence	Nicosulfuron + rimsulfuron	After Emergence
Carfentrazone	After Emergence	Rimsulfuron	After Emergence
Isoxaflutole + thiencarbazone	Before Emergence	Saflufenacil	Before Emergence
Acetochlor + clopyralid + flumetsulam	Before Emergence	Dimethenamid-P + saflufenacil	Before Emergence
Atrazine	After Emergence	Glyphosate followed by glyphosate	After Emergence
Count=32			

Table 6. List of herbicide treatments used in the 2011 analysis, grain sorghum.

Herbicide treatment	Time of application
Atrazine	Before Emergence
Atrazine	After Emergence
S-metolachlor+Atrazine	Before Emergence
S-metolachlor	Before Emergence
2,4-D	After Emergence
Atrazine +Dimethenamid, -P	Before Emergence
Dimethenamid-P	Before Emergence
Prosulfuron AE	After Emergence
Atrazine + Mesotrione+ S-metolachlor	Before Emergence
Propazine	Before Emergence
Alachlor+Atrazine	Before Emergence
Dicamba	After Emergence
Bromoxynil	After Emergence
Acetochlor+Atrazine	Before Emergence
Fluroxypyr AE	After Emergence
Carfentrazone	After Emergence
Halosulfuron	After Emergence
Count = 17	

Table 7. List of herbicide treatments used in the 2011 analysis, sweet corn.

Herbicide treatment	**Time of Application**
Atrazine	Before Emergence
Acetochlor + atrazine	Before Emergence
S-metolachlor + mesotrione + atrazine	Before Emergence
S-metolachlor + atrazine	Before Emergence
Acetochlor	Before Emergence
Atrazine + dimethenamid-P	Before Emergence
Simazine	Before Emergence
S-metolachlor	Before Emergence
Pendimethalin	Before Emergence
Dimethenamid, -P	Before Emergence
Carfentrazone	After Emergence
Atrazine	After Emergence
2,4-D	After Emergence
Mesotrione	After Emergence
Tembotrione + safener	After Emergence
Topramezone	After Emergence
Count = 16	

Table 8. Infestation (percent acres) and potential damage (percent yield loss) by weed species and by FRR – from 2010 data.

Weed Code	Common name(s)	Heartland		Northern Crescent		Northern Great Plains		Prairie Gateway		Rest of Nation[1]	
		PI[2]	PR[3]	PI	PR	PI	PR	PI	PR	PI	PR
ABUTH	Velvetleaf	54	30	20	45	13	20	32	20	25	30
AGRRE	Quackgrass	3	9	18	38	1	1	1	2	2	27
AMAPA	Palmer pigweed	13	43	0	0	20	30	65	38	44	50
AMATZ	Common/Tall waterhemp	49	26	95	55	58	25	42	24	39	32
AMAZZ	Pigweeds (all others)	51	30	80	50	55	30	45	40	49	41
AMBTR	Giant ragweed	33	49	8	78	3	25	3	11	10	49
AMBEL	Other ragweeds	24	33	65	78	3	15	4	12	21	32
BRAPP	Broadleaf signalgrass	2	10	0	0	0	0	0	0	26	27
CASOB	Sicklepod	0	0	0	0	0	0	0	0	16	20
CHEAL	Common lambsquarters	67	31	1	10	18	20	23	35	9	17
CIRZZ	Thistles	7	7	25	35	34	28	18	16	10	25
CYPZZ	Nutsedges	12	23	21	18	1	5	10	13	23	22
DATST	Jimsonweed	2	13	3	25	0	0	0	0	2	18
DIGZZ	Crabgrass	26	15	25	25	5	5	35	15	50	28
ECHCG	Barnyardgrass	25	22	8	25	48	23	34	16	31	32
ELEIN	Goosegrass	8	12	3	40	1	1	3	6	20	25
ERICA	Horseweed / Marestail	36	16	33	30	20	20	23	16	35	17
HELZZ	Sunflower(s)	22	50	0	0	13	35	11	25	4	30
IPOZZ	Morningglories	40	25	5	20	5	15	10	14	62	36
KCHSC	Kochia	8	23	0	0	58	33	47	35	8	21
PANCA	Witchgrass	5	7	2	10	1	5	5	3	21	16
PANDI	Fall panicum	28	25	18	20	8	10	11	6	18	21
PANTE	Texas panicum	1	23	0	0	0	0	0	0	12	27
POLZZ	Smartweeds	20	28	13	28	3	5	3	3	9	18
SETZZ	Foxtails	81	38	80	45	55	18	57	23	27	21
SIDZZ	Sidas (prickly/arrowleaf)	21	12	4	13	0	0	2	0	25	13
SINAR	Wild mustard	10	10	5	15	5	10	2	10	7	23
SOLZZ	Nightshades	24	12	18	25	28	8	23	8	9	13
SORHA	Johnsongrass	10	40	4	28	1	20	17	29	17	36
SORVU	Shattercane	13	30	4	18	5	20	13	29	4	40
XANZZ	Cockleburs	36	34	4	35	13	15	14	12	14	28

[1] *Rest of Nation = combination of the following USDA FRR: Basin and Range, Eastern Uplands, Fruitful Rim, Mississippi Portal, Southern Seaboard.*
[2] *PI=percent infested crop acres.*
[3] *PR=percent yield reduction.*

Table 9. Summary of potential farm-gate impact of the loss of atrazine in U.S. field corn production for current atrazine use acres and total field corn acres by FRR and as a national weighted average – Scenario 1 – Non-triazine – increasing glyphosate acres[1].

	Heartland	**Northern Crescent**	**Northern Great Plains**	**Prairie Gateway**	**Rest of Nation**	**Total U.S.**
Current* atrazine use acres						
Cost ($/acre)[2]	-4.16	-8.89	0.37	-3.56	0.12	
Yield (bu/acre)	-15.26	-10.76	-6.73	-4.41	-11.40	
Production ($/acre)	-57.23	-40.35	-25.25	-16.55	-42.74	
Net change ($/acre)	-53.07	-31.46	-25.62	-12.99	-42.85	
All field corn acres						Weighted Average
Cost ($/acre)	2.66	1.25	1.13	0.26	1.74	1.80
Yield (bu/acre)	-9.20	-4.97	-1.76	-2.80	-8.80	-6.40
Yield (%)	-5.26	-3.45	-1.39	-1.84	-6.24	
Production ($/acre)	-34.48	-18.63	-6.59	-10.49	-33.02	-24.02
Net change ($/acre)	-37.14	-19.88	-7.71	-10.74	-34.76	-25.82
Overall impact to Region						Total
Total field corn acres	49,313,200	11,017,500	6,183,700	11,783,600	7,881,000	86,179,000
Regional impact ($)	-1,831,553,890	-219,008,619	-47,705,700	-126,555,864	-273,904,155	-2,498,728,227

[1] Based on corn price of $3.75 per bushel.

[2] Cost changes do not include additional application costs, only the cost of alternative single-pass herbicide products.

*Based on 2009 use and reporting data.

Table 10. Summary of potential farm-gate impact of the loss of atrazine in U.S. field corn production for current atrazine use acres and total field corn acres by FRR and as a national weighted average – Scenario 2 – Non-triazine – 2009 glyphosate acres[1].

	Heartland	**Northern Crescent**	**Northern Great Plains**	**Prairie Gateway**	**Rest of Nation**	**U.S.**
User changes						
Cost ($/acre)[2]	-1.46	-5.54	2.24	-1.32	0.07	
Yield (bu/acre)	-17.55	-16.30	-10.95	-5.74	-17.53	
Production ($/acre)	-65.80	-61.14	-41.05	-21.51	-65.75	
Net change ($/acre)	-64.34	-55.60	-43.29	-20.20	-65.82	
Region changes						Weighted Average
Cost ($/acre)	-0.29	-2.56	0.59	-0.23	0.05	-0.48
Yield (bu/acre)	-10.57	-7.53	-2.86	-3.64	-13.55	-7.71
Yield (%)	-6.04	-5.23	-2.27	-2.39	-9.61	
Production ($/acre)	-39.65	-28.22	-10.71	-13.64	-50.79	-28.93
Net change ($/acre)	-39.36	-25.66	-11.30	-13.40	-50.84	-28.45
Overall impact to Region						Total
Regional acres	49,313,200	11,017,500	6,183,700	11,783,600	7,881,000	86,179,000
Regional impact ($)	-1,941,004,537	-282,758,629	-69,844,892	-157,923,807	-400,707,475	-2,852,239,339

[1] Based on corn price of $3.75 per bushel.

[2] Cost changes do not include additional application costs, only the cost of alternative single-pass herbicide products.

Table 11. Summary of potential farm-gate impact of the loss of atrazine and simazine in U.S. sweet corn.

		Target Acres		Regional Planted Acres	
FRR	**Planted acres**	**Average Cost Change ($/acre)**	**% Yield Change**	**% Cost Change[1]**	**% Yield Change**
Northern Crescent	241,012	-1.76	-32.70	-1.10	-20.45
Heartland	106,293	2.44	-26.93	1.86	-20.47
Fruitful Rim	189,308	0.85	-25.49	0.66	-19.62
Rest of Nation	47,093				
Total	583,706				

[1] Cost changes do not include additional application costs, only the cost of alternative single-pass herbicide products.

Table 12. Summary of potential farm-gate impact of the loss of atrazine and propazine in U.S. grain sorghum[1] .

	Prairie Gateway	**Rest of Nation[2]**	**U.S.**
User changes			
Cost ($/acre)	-4.04	-4.04	
Yield (bu/acre)	-17.72	-17.72	
Production ($/acre)	-62.03	-62.03	
Net change ($/acre)	-57.98	-57.98	
Region changes	Prairie Gateway	Rest of Nation	Weighted Average
Cost ($/acre)	-2.99	-2.99	-2.99
Yield (bu/acre)	-13.11	-13.11	-13.11
Yield (%)	-20.49	-20.49	-20.49
Production ($/acre)	-45.90	-45.90	-45.90
Net change ($/acre)	-42.91	-42.91	-42.91
Overall impact to Region	Prairie Gateway	Rest of Nation	Total
Regional acres	5,527,000	1,363,430	6,890,430
Regional impact ($)	-237,160,807	-58,504,100	-295,664,906

[1] Based on sorghum price of $3.50 per bushel.

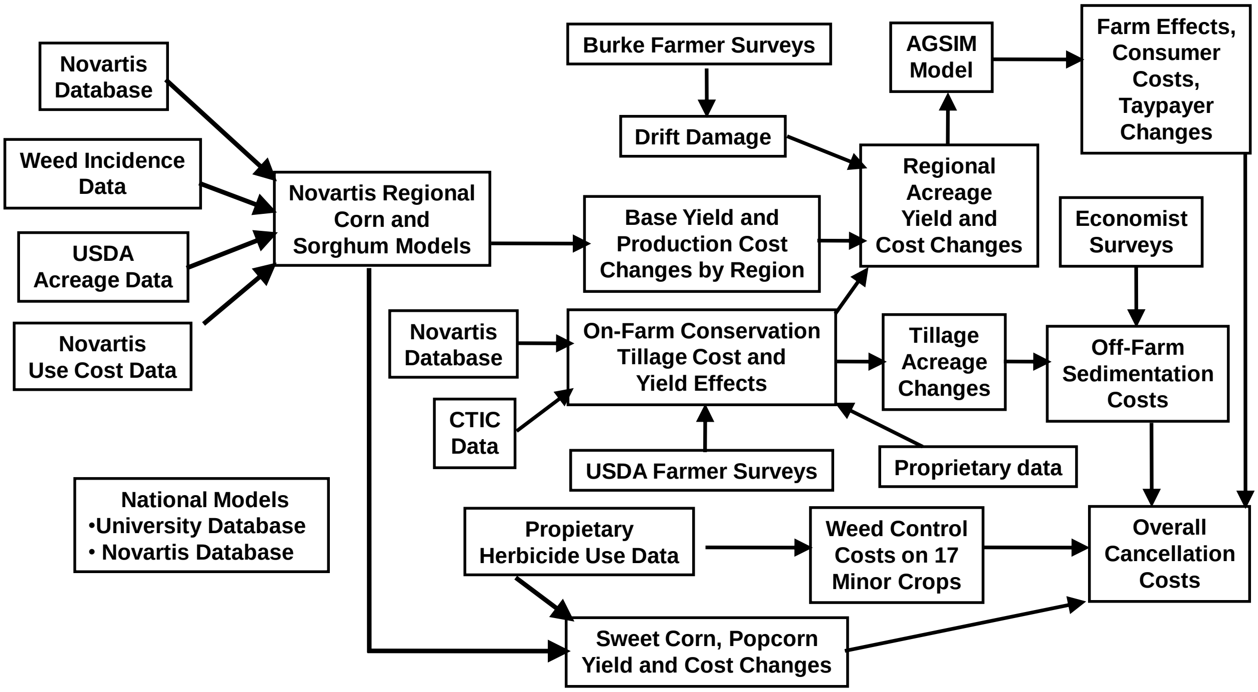
[2] Cost and yield of the Prairie Gateway assessment were applied to sorghum acres in the Rest of Nation.

Table 13. Field corn herbicide use with atrazine.

Active Ingredient	% Herbicide Base Acres Applied with Atrazine
2,4-D	74.9
Acetochlor	73.4
Alachlor	82.5
Ametryn	100.0
Atrazine	100.0
Bentazon	100.0
Bromoxynil	80.3
Carfentrazone-ethyl	40.2
Clethodim	70.7
Clopyralid	38.0
Dicamba	47.9
Diflufenzopyr	45.8
Dimethenamid	99.0
Dimethenamid-P	52.1
Flufenacet	41.0
Flumetsulam	38.8
Flumiclorac	36.2
Flumioxazin	78.9
Fluroxypyr	9.7
Fluthiacet-methyl	35.6
Foramsulfuron	17.2
Glufosinate	66.5
Glyphosate	50.2
Halosulfuron	52.5
Imazapyr	90.5
Imazethapyr	85.4
Iodosulfuron	81.6
Isoxaflutole	55.4
Linuron	100.0
Mesotrione	82.4
Metolacholor	87.1
Metolachlor-S	87.7
Nicosulfuron	68.8
Paraquat	77.3
Pendimethalin	66.8
Primisulfuron	72.9
Prosulfuron	85.7

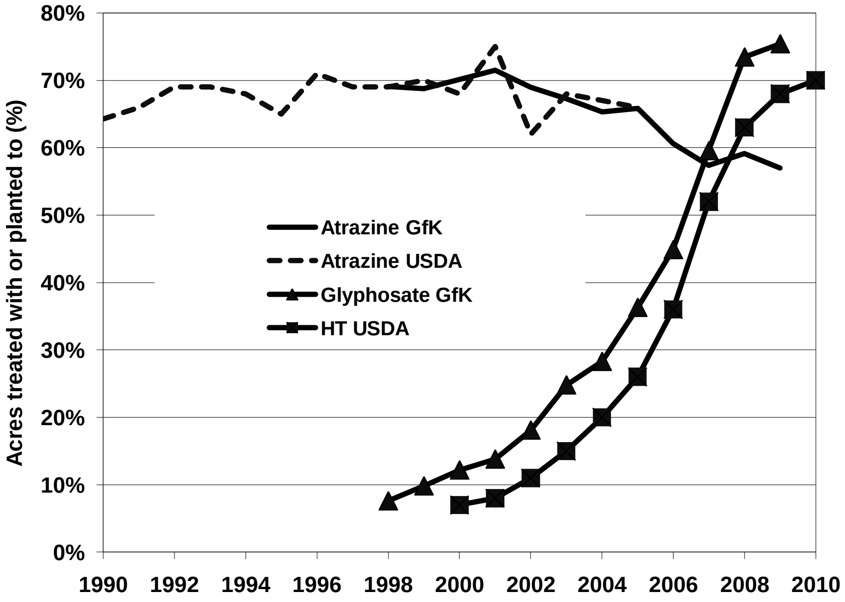
Rimsulfuron	66.8
Simazine	80.5
Tembotrione	52.9
Thiencarbazone-methyl	61.0
Thifensulfuron	69.0
Topramezone	68.4
Tribenuron-methyl	0.0
2009 Total	**2009 Average 57.9**

Figure 1. Overview of Benefits Assessment Process, 1995.



Adapted from Bridges, D.C. 1998. A simulation analysis of the use and benefits of triazine herbicides in *Triazine Herbicides Risk Assessment* ed. L.G. Ballentine, J.E. McFarland and D.S. Hackett, American Chemical Society, Washington, DC. 480 pgs.

Figure 2. Use of atrazine, glyphosate and herbicide tolerant crops in U.S. field corn production.



Sources: atrazine use (GfK Kynetec and USDA); glyphosate use (GfK Kynetec); herbicide tolerant corn (USDA).

Embargoed until Wednesday, 9 November 2011, 2pm central

Figure 3. Overview of Current "Behind the Farm Gate" Benefits Assessment Process, 2011.

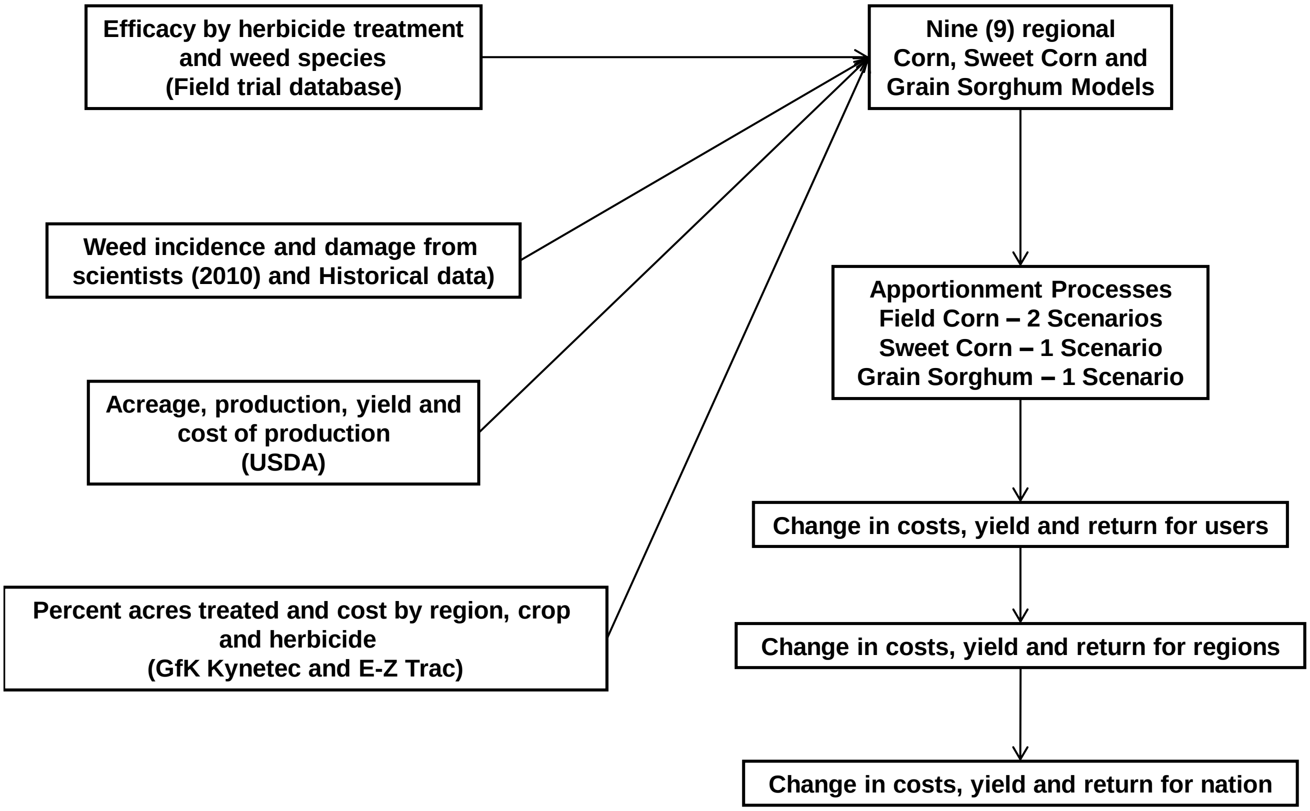
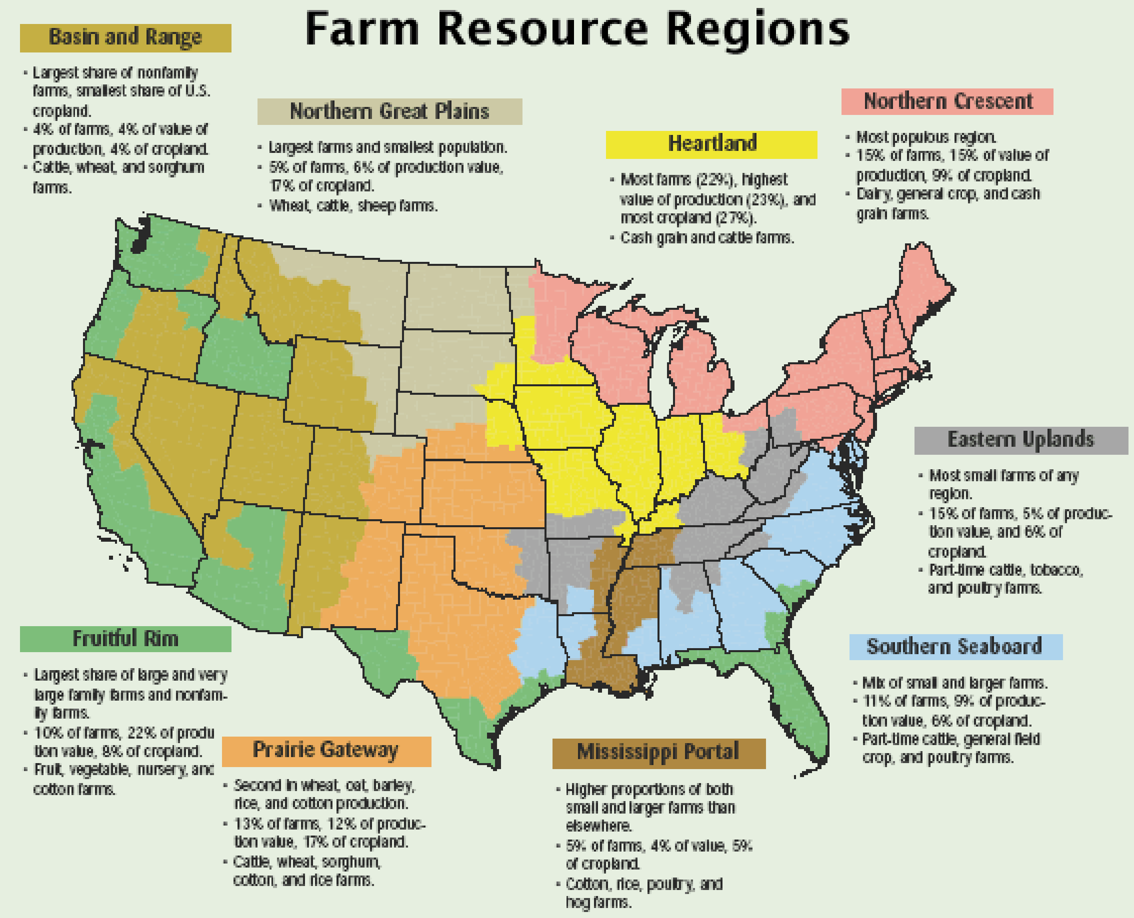


Figure 4. USDA Farm Resource Regions, FRR.



Farm Resource Regions

Basin and Range

- Largest share of nonfamily farms, smallest share of U.S. cropland.
- 4% of farms, 4% of value of production, 4% of cropland.
- Cattle, wheat, and sorghum farms.

Northern Great Plains

- Largest farms and smallest population.
- 5% of farms, 6% of production value, 17% of cropland.
- Wheat, cattle, sheep farms.

Heartland

- Most farms (22%), highest value of production (23%), and most cropland (27%).
- Cash grain and cattle farms.

Northern Crescent

- Most populous region.
- 15% of farms, 15% of value of production, 9% of cropland.
- Dairy, general crop, and cash grain farms.

Eastern Uplands

- Most small farms of any region.
- 15% of farms, 5% of production value, and 6% of cropland.
- Part-time cattle, tobacco, and poultry farms.

Southern Seaboard

- Mix of small and larger farms.
- 11% of farms, 9% of production value, 6% of cropland.
- Part-time cattle, general field crop, and poultry farms.

Fruitful Rim

- Largest share of large and very large family farms and nonfamily farms.
- 10% of farms, 22% of produ tion value, 8% of cropland.
- Fruit, vegetable, nursery, anc cotton farms.

Prairie Gateway

- Second in wheat, oat, barley, rice, and cotton production.
- 13% of farms, 12% of production value, 17% of cropland.
- Cattle, wheat, sorghum, cotton, and rice farms.

Mississippi Portal

- Higher proportions of both small and larger farms than elsewhere.
- 5% of farms, 4% of value, 5% of cropland.
- Cotton, rice, poultry, and hog farms.

From USDA-ERS. 2000. Farm Resource Regions. Agricultural Information Bulletin Number 760. United States Department of Agriculture, Washington, DC.

Figure 5. Overview of current assessment data requirements and computational framework.

Required Input Data

1. Efficacy by herbicide treatment and weed species (Source=field trial database).
2. Weed incidence and damage from weed scientists (2010)and historical, published data
3. Acreage, production, yield and cost of production (Source=USDA ERS).
4. 2009 percent treated acres and cost by region, crop and herbicide (Source=GfK Kynetec and E-Z Trak).
5. Weed targets by herbicide treatment and FRR.

Computational Process

1. Basic underlying computations
2. Substitution analysis (1-way) using 2009 percent treated acres
   - For each apportionment scenario (2 for field corn, 1 each for grain sorghum and sweet corn) calculate cost, yield and return changes for:
     - Users
     - Regions
     - Nation
3. Potential value (1-way) – net returns to region for each herbicide treatment (applied to all acres in region).
4. Potential value (2-way) – net returns to region for all 2-way combinations (applied to all acres in region).
5. Potential value (3-way) – net returns to region for all 3-way combinations (applied to all acres in region).

Figure 6. Use of corn herbicides with atrazine, U.S. 2009 crop.

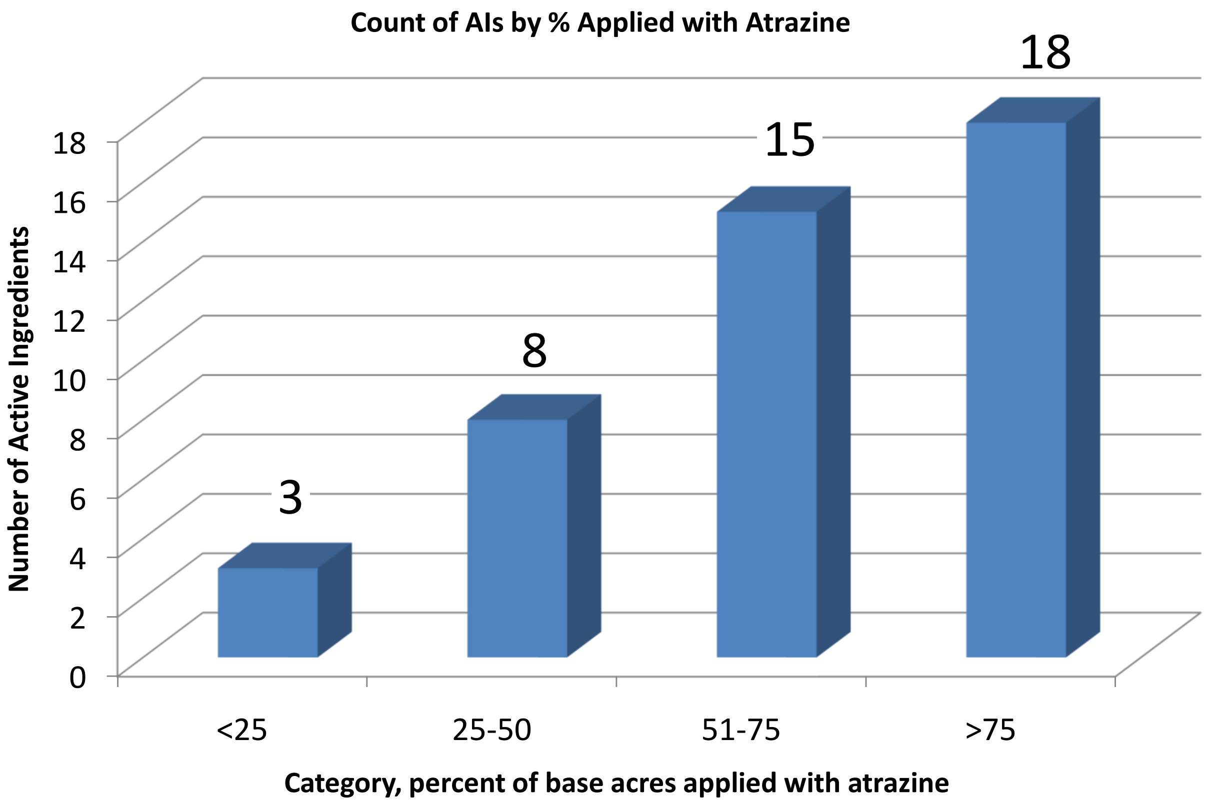


Figure 7. Importance of atrazine, simazine and glyphosate to Heartland FRR field corn farmers.

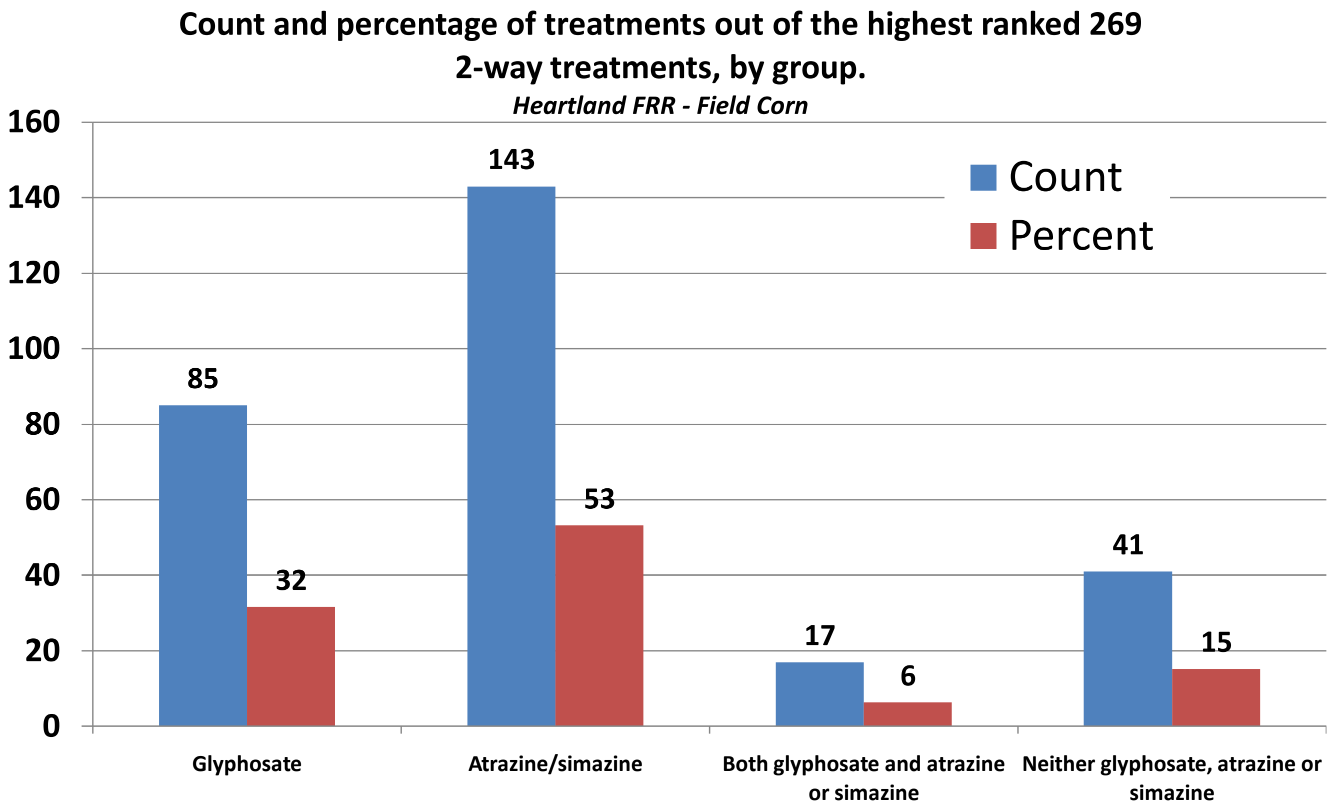
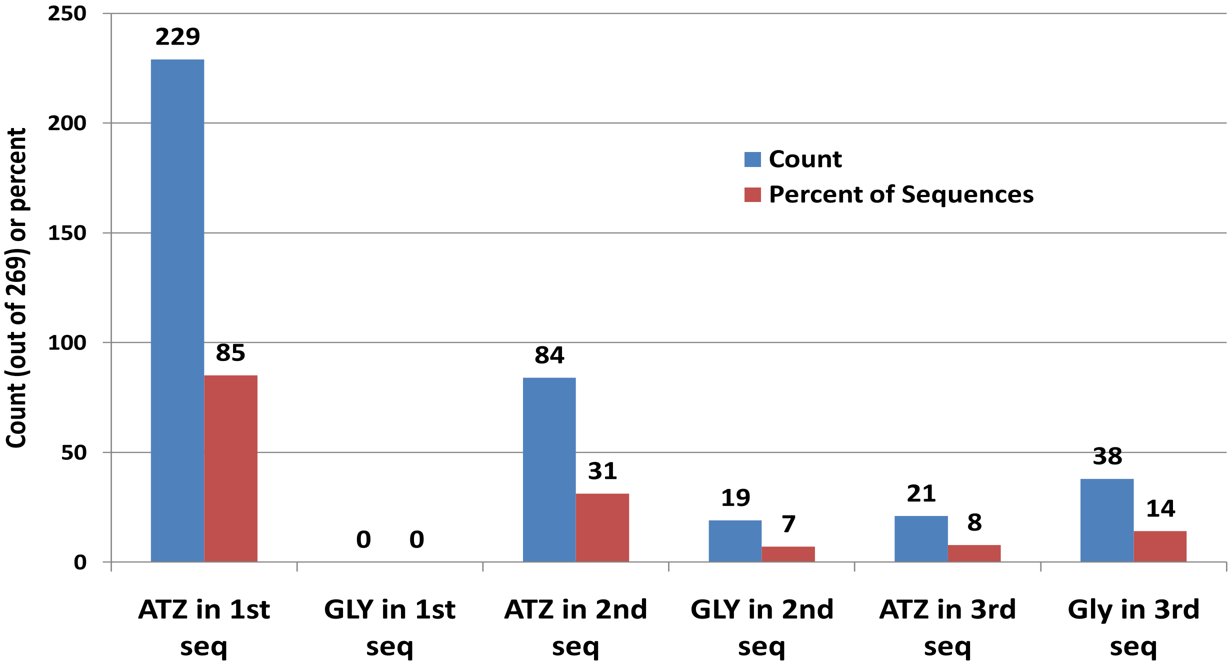


Figure 8. Importance of atrazine in sequences, 3-way treatments, Heartland FRR Field Corn.



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