TWENTY YEARS OF UNIVERSITY CORN YIELD DATA: WITH AND WITHOUT ATRAZINE.
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Herbicide efficacy studies reporting corn yields published in the North Central Weed Science Society Research Report were analyzed to calculate average corn yields for treatments either containing atrazine or not containing atrazine. To prevent unequal comparisons, studies and treatments had to meet conservative selection criteria in order to be included in the analysis. Treatments had to control both broadleaf and grass weeds (normally containing at least two active ingredients), and active ingredients had to be currently registered for use and used at label rates. For the 20-year period, 1986-2005, 236 qualifying studies were identified, with a total of 5,871 qualifying treatments. For the period 1986-1995, corn yielded an average 6.3 bushels/acre higher or 5.9% higher with atrazine than without. For the period 1996-2005, corn yielded an average 5.4 bushels/acre higher or 4.6% higher with atrazine. For the entire 20-year period, the average yield with atrazine was 5.7 bushels/acre higher or 5.1% higher with atrazine than without. Corn yields with atrazine continued to be higher than with non-atrazine treatments as new active ingredients and new technologies such as herbicide-tolerant corn hybrids were introduced. University researchers have increasingly added atrazine to new active ingredients to improve weed control. In 1986, 55% of all evaluated treatments in studies contained atrazine. As many new active ingredients were evaluated, treatments containing atrazine dropped to 17% in 1995. However, by 2005, 79% of all treatments in the studies evaluated contained atrazine. Considering the value of increased corn yields with atrazine and the lower cost of atrazine compared to alternatives, atrazine use added an estimated $25.74 per acre income to farmers in 2005, with a total U.S. benefit to farmers of $1.39 billion.

Introduction

In 1996, on behalf of the Triazine Network, Fawcett Consulting prepared for the Special Review Division of USEPA an analysis of corn yields with and without atrazine herbicide, using university studies annually published in the Research Report of the North Central Weed Science Society (Submission to the docket OPP-3-0000-60). Data for the 10-year period 1986 to 1995 were analyzed to determine corn yield benefits from the use of atrazine for weed control. In order to determine if beneficial yield impacts of atrazine treatments continued in more recent years, a similar data analysis was later conducted from NCWSS Research Reports for the years 1996 through 2005, the last year the Research Report was published. As many studies do not report yield data, only studies reporting yields can be analyzed. Because some universities never report yields in the Research Report and some report yields on only a few studies, most studies available for analysis are from Wisconsin, Minnesota, Illinois, Iowa, and Nebraska, with a few studies from South Dakota, Kansas, and Indiana. In order to eliminate potential unequal comparisons between herbicide treatments, selection criteria were developed for studies used, and for treatments within studies. In absence of conservative selection criteria, yield summaries would not be realistic for several reasons. For example, rates lower than label rates are sometimes tested, resulting in low yields. Or single active ingredient treatments included as standards may not control grasses or broadleaf weeds.

Study Selection Criteria

The following criteria were used to select studies and treatments within studies:

1. The study must be designed to evaluate weed control. Some studies have no weeds or are hand weeded and investigate other factors such as crop safety, and thus are not suitable for this summary.

2. The study must evaluate both grass and broadleaf weeds. Some studies are seeded to single weed species (often grasses such as woolly cupgrass and wild proso millet) and thus are not suitable to measure the contribution of atrazine.
3. Atrazine must be included in at least 10%, but no more than 90% of treatments, with at least 2 atrazine or non-atrazine treatments. This criterion is to avoid situations where only one or two treatments (either atrazine or non-atrazine) would be used to calculate an average yield from a test, increasing the influence of experimental error. If a study involves more than one method of application (such as preemergence or postemergence), representative atrazine and non-atrazine treatments should be included for each application method. For example, due to dry weather, all preemergence treatments might fail, while postemergence treatments might be effective, biasing comparisons if one method of application lacked either atrazine or non-atrazine treatments.

Treatment Criteria

1. The treatment must have both grass and broadleaf activity. This usually means that at least 2 active ingredients are used. Often single ingredient standards are included in studies, producing low yields due to controlling only part of the weed spectrum.
2. All active ingredients included in treatments must be registered for use at the time of the analysis. Active ingredients which were experimental at the time of the study, but were registered at the time of the analysis, are included.
3. Rates must be within current label ranges. Studies early in the development of experimental herbicides often test several rates, including ineffective low rates, and rates above eventual label rates. As atrazine label rates have been reduced, some treatments in past studies have atrazine rates above current label rates. These treatments are not included.
4. If additional weed control measures such as cultivation are used, data is included only if all treatments received the additional measure.

Yield Results

Table 1 shows data summaries for 88 corn experiments conducted between 1986 and 1995. Average yield differences for atrazine-containing treatments and non-atrazine treatments are reported for studies in each year. Both bushel/acre differences in yields, as well as percentage differences in yields, are presented. The average yield increase with atrazine for this 10-year period was 6.3 bu/A, for a 5.9% increase in yield compared to non-atrazine treatments. Average yields with atrazine were higher in 73 studies, lower in 14 and equal in one study.

Table 2 shows data summaries for 148 studies for the years 1996 through 2005. Over the 10-year period, the average yield increase with atrazine was 5.4 bu/A, for a 4.6% yield increase compared to non-atrazine treatments. Thus, despite the introduction of numerous new herbicide active ingredients to the marketplace since 1995, atrazine still produces weed control and yield benefits, compared to alternative herbicides. For the entire 20-year period of 1986 through 2005, the average yield increase with atrazine was 5.7 bu/A or 5.1%.

Statistical Analysis

Figure 1 shows the distribution of corn yields as a percent difference for yields with atrazine versus yields without atrazine. The data are not normally distributed, being skewed to the right. Also, five data points might be considered outliers. All of these five data points come from trials containing ALS-resistant common waterhemp biotypes, where ALS herbicides applied to ALS-tolerant corn failed to control the weed, resulting in lowered yields. Inclusion of atrazine resulted in dramatically higher yields.

The mean percentage yield increase with atrazine for the 1986-2005 period was 5.09%, with a standard deviation of 11.99, standard error of the mean of 0.78, upper and lower 95% confidence intervals of 6.63 and 3.55, respectively, and n of 236. As a parametric test may not be considered appropriate due to non-normal distribution of data, data were analyzed both by t-test and Wilcoxon Signed-Rank test. Both tests result in highly significant probabilities that the percent increase in yield with atrazine is greater than 2.0. The result of the t-test is significant, while the Wilcoxon Signed-Rank test is not significant that the percent increase in yield is greater than 3.0.

Herbicide-tolerant Crops

The introduction of herbicide-tolerant corn hybrids is a major technological change since the 1986-1995 data summary. During the 1996-2005 period, corn hybrids tolerant to glyphosate, glufosinate, sethoxydim and the imidazolinone herbicides imazethapyr and imazapyr have been introduced. To determine if inclusion of atrazine with these herbicides on herbicide-tolerant corn hybrids influenced corn yields, an analysis of data from 1996-2005 was conducted using the previously described study and treatment criteria. Table 3 shows results of the herbicide-tolerant corn comparisons. Inclusion of atrazine increased average corn yields on all categories of herbicide-tolerant corn. Yields were increased by 10.6, 4.9, 4.8, and 2.0 bu/A with imidazolinone, glufosinate, sethoxydim, and glyphosate-tolerant corn hybrids, respectively. Atrazine was particularly beneficial with imidazolinone-tolerant corn. In one experiment (1997-2), tall waterhemp was determined to be resistant to ALS herbicides, causing poor weed control with the normally broad-spectrum imazethapyr + imazapyr treatment. Low rates of atrazine included with the imidazolinone treatments increased yields by 52.5 bu/A. A subsequent study at the same location in 2002 demonstrated a 46.8 bu/A yield benefit from atrazine. Atrazine is an important tool in weed resistance management, as it has a different mode of action than any of the products used on herbicide-tolerant corn. As adoption of these corn hybrids increases, atrazine will become more important in both improving control of certain weed species and in preventing the increase of herbicide-resistant weed biotypes.

Application Practices

Herbicide use practices have changed during the 20 years encompassed by data in these analyses, including rates and numbers of active ingredients used and number of herbicide applications made. Possible changes in these factors related to atrazine usage were investigated by comparing all 1986 studies to all 2001 and 2005 studies (Because 2002-2005 studies are dominated by Minnesota studies with similar designs, 2001 studies representing more states and study designs were also analyzed.), recording number of active ingredients per treatment, number of application trips per treatment, and atrazine rates per acre. Results of the analysis are reported in Table 4. Average number of active ingredients per treatment and application trips used in research studies have increased during the period. Considering non-atrazine treatments, average number of active ingredients increased from 2.09 to 2.64, and application trips increased from 1.45 to 1.61, comparing 1986 to 2001. Fewer average application trips were made for atrazine-containing treatments, both in 1986 and 2001. In 2001, an average 1.53 application trips were made with atrazine-containing treatments compared to 1.61 application trips for non-atrazine treatments. In 2005, due to Minnesota study designs, slightly more application trips were made for atrazine-containing treatments (1.54 vs 1.40 for non-atrazine treatments). Average atrazine application rates declined from 1.17 lb/A in 1986 to 0.88 lb/A in 2001 and to 0.61 lb/A in 2005. This represents a 48% rate decline over the period.

Atrazine Use with New Actives

Atrazine remains an important weed management tool, despite the introduction of numerous new herbicide active ingredients and introduction of new technology such as herbicide-tolerant crops.

Atrazine is applied with most new active ingredients either as a component of package mixes or in tank mixes. Table 5 shows a list of 57 herbicide package mix products containing atrazine. Seventeen different active ingredients are found in these products. As new active ingredients have been registered for use, manufacturers have been quick to combine them with atrazine in package mixes and to label them for use with atrazine in tank mixes. University researchers have also dramatically increased evaluations of atrazine in combination with other active ingredients. This increase has occurred both due to industry protocols that have requested that new actives be evaluated with atrazine and researchers' own initiatives to try to overcome weaknesses of new actives on specific weeds.

Table 6 shows an analysis of percent of all treatments meeting treatment selection criteria that contained atrazine for the 20 years of studies analyzed. This analysis contains more data than was used in the yield analysis, as studies that could not be used in the yield analysis due to too few non-atrazine treatments (or too few atrazine treatments) could still appropriately be used in this analysis. In recent years many studies reporting yields could not be used in atrazine yield benefit calculations because all treatments or all except one treatment contained atrazine. For example, in 2005, 20 NCWSS Research Report studies reported yields. Eleven were suitable for inclusion in calculating atrazine yield benefits, while seven could not be used because they had atrazine included in 100% of treatments or had only one non-atrazine treatment. Two were excluded because of not meeting other selection criteria. In the late 1980s about 60% of treatments evaluated in university studies contained atrazine. As many new active ingredients were evaluated in the 1990s, the percent of treatments containing atrazine steadily declined to a low of 17% in 1995. However, for the next decade, use of atrazine steadily increased until 80% of all treatments evaluated in 2004 contained atrazine. This dramatic increase in inclusion of atrazine with other active ingredients came about as university and industry researchers observed the shortcomings of new actives and turned to atrazine to solve these shortcomings.

Researchers searching for improved weed control are applying more active ingredients and making more applications today than in the past. Even though more active ingredients and more applications are being used, addition of atrazine still produces corn yield increases, compared to non-atrazine treatments. Atrazine-containing treatments averaged 5.4 bushels per acre more yield than non-atrazine treatments for the 1996-2005 period, compared to 6.3 bushel per acre advantage in the 1986-1995 period. Some of the biggest yield increases produced by atrazine were in herbicide-tolerant corn trials, where atrazine controlled herbicide resistant weed biotypes. Besides improving yield, atrazine use on such hybrids helps to prevent selection for herbicide resistant weeds.

Atrazine Cost

Atrazine has produced weed control and yield benefits to farmers at a remarkably low cost. Atrazine sold in package mix products often costs less than when purchased alone. To determine the average cost of atrazine to farmers, the costs of companion active ingredients, when purchased separately, were subtracted from costs of respective package mix products containing atrazine, using the University of Minnesota 2005 price lists. Table 7 shows the costs of atrazine per pound active in three common atrazine-containing package mix products, and the cost of atrazine when purchased alone. The average cost of the atrazine in the four sources is $2.18 per pound active ingredient. Table 8 compares the average atrazine cost to the average per acre costs of 14 non-atrazine broadleaf control herbicides in corn according to the University of Minnesota publication. At the rate of 1.13 lb per acre, the average U.S. atrazine rate used in the 2005 National Agricultural Statistics Service (NASS) survey, the cost of atrazine per acre is only $2.46. The only broadleaf herbicide less expensive is 2,4-D, at $1.63 per acre. The corn injury and drift risk with this herbicide limit its use to only a small acreage. The next closest cost competitor is Aim at $2.70 per acre. This herbicide controls only a few specific species and does not compete with atrazine for that reason. The average per acre cost of non-atrazine alternatives of $12.34 is $9.88 per acre more than atrazine.

Atrazine users receive economic benefits from higher yields and from lower herbicide costs. Using the 2005 average yield increase with atrazine of 6.1 bu/A and the USDA Target Price for corn of $2.60 per bushel (the effective price received by farmers participating in USDA Farm Programs), atrazine users gained added income of $15.86 per acre. Adding the savings of lower cost of atrazine versus alternatives of $9.88 per acre, corn farmers using atrazine received a total economic benefit of $25.74 per acre. NASS reports that 82 million acres of corn were planted in 2005. If 66% of U.S. corn was treated with atrazine (NASS survey data from 2005), then about 54.1 million acres of corn would have been treated with atrazine in the U.S. in 2005. Using the $25.74 per acre value of increased income for atrazine use, an estimated total economic benefit to U.S. farmers of about $1.39 billion occurred in 2005.

Conclusions

Analysis of university weed control studies published in the NCWSS Research Report for the period 1996-2005 shows a corn yield advantage for treatments including atrazine of 5.4 bushel per acre or 4.6% compared to non-atrazine treatments. This yield benefit is similar to a yield benefit of 6.3 bushels per acre or 5.9% calculated for the previous 10 years of study. Despite the availability of many new herbicide active ingredients, atrazine continues to produce economic benefits for corn farmers. This has occurred despite the practice of including more active ingredients per treatment (in absence of atrazine) and making more herbicide applications during the 1996-2005 period. Average atrazine application rates in these university studies declined from an average 1.17 lb/acre in 1986 to 0.61 lb/acre in 2005. Atrazine is especially useful on herbicide-tolerant corn hybrids, where it controls herbicide-resistant weeds and helps to prevent future increases in herbicide-resistant weeds. Atrazine brings these benefits at a remarkably low cost, with the cost of the average 1.13 lb atrazine used in 2005 by U.S. corn farmers being $2.46 per acre, compared to $12.34 per acre, the average cost of 14 alternative broadleaf control herbicides in corn. Considering added income from higher yields and lower herbicide costs, atrazine use resulted in added income to farmers of $25.74 per acre in 2005, with a total U.S. benefit to farmers of about $1.39 billion.

Acknowledgements

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