Would banning atrazine benefit farmers?

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Atrazine, an herbicide used on most of the US corn (maize) crop, is the subject of ongoing controversy, with increasing documentation of its potentially harmful health and environmental impacts. Supporters of atrazine often claim that it is of great value to farmers; most recently, Syngenta, the producer of atrazine, sponsored an ''Atrazine Benefits Team'' (ABT) of researchers who released a set of five papers in 2011, reporting huge economic benefits from atrazine use in US agriculture. A critical review of the ABT papers shows that they have underestimated the growing problem of atrazine-resistant weeds, offered only a partial review of the effectiveness of alternative herbicides, and ignored the promising option of non-chemical weed management techniques.

In addition, the most complete economic analysis in the ABT papers implies that withdrawal of atrazine would lead to a decrease in corn yields of 4.4% and an increase in corn prices of 8.0%. The result would be an increase in corn growers' revenues, equal to US$1.7 billion annually under ABT assumptions. Price impacts on consumers would be minimal: at current levels of ethanol production and use, gasoline prices would rise by no more than US$0.03 per gallon; beef prices would rise by an estimated US$0.01 for a 4-ounce hamburger and US$0.05 for an 8-ounce steak. Thus withdrawal of atrazine would boost farm revenues, while only changing consumer prices by pennies.

Keywords: Agriculture, Atrazine, Corn, Economic impacts, Herbicides, Weed management

Would Banning Atrazine Benefit Farmers?

Every year, atrazine is applied to tens of millions of acres of corn (maize) grown in the United States, making it one of the world's most widely used agricultural chemicals.[1] A powerful, low-cost herbicide, atrazine is also the subject of persistent controversy. It is an endocrine disrupter, causing feminization in male frogs and other species at very low concentrations;[2] it harms immune systems in exposed aquatic wildlife;[3] and exposure to it during pregnancy may increase risks of birth defects and low birth weight in humans.[4,5] Produced by Syngenta, a European chemical company, atrazine is subject to strict regulation that effectively prevents its use in Europe* – but it remains a staple of American agriculture.

While the health and environmental effects of atrazine have been researched in depth, there has been only limited analysis of the economic impacts of atrazine use. In an earlier article in this journal, one of us (Ackerman) found that supporters of atrazine generally claimed that it added 6% or less to corn yields per acre.[7] He also found that a pro-atrazine economic study sponsored by Syngenta contained serious, elementary errors, while more careful and detailed studies suggested that atrazine might increase corn yields by as little as 1–3%.

The atrazine debate has continued and intensified in recent years. A group of midwestern water districts filed a class action suit against Syngenta, seeking to recover the high costs of removing atrazine from their municipal water supplies, and won a US$105 million settlement – but not an admission that any harm had been done to them.[8,9] The Triazine Network, a pro-atrazine association of agribusiness and farm organizations, has sounded the alarm about what it calls ''atrazine alarmists,'' i.e. those who have questioned the use of this chemical.†

Syngenta, meanwhile, assembled an ''Atrazine Benefits Team'' (ABT) of researchers, who reported finding huge benefits from atrazine use in US agriculture. One of them alleges that their work has made Ackerman's 2007 article outdated.[10] ‡

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* Atrazine has been excluded from the re-registration process in the European Union since 2003 owing to the manufacturer's inability to demonstrate that its use would not result in groundwater concentrations greater than 0.1 μg/l.[6]

† See http://agsense.org/atrazine-alarmists/.

‡ We agree that Ackerman's earlier work is dated in one respect: it emphasized that fact that Germany and Italy have continued to have high corn yields after ending the use of atrazine; newer information suggests that many European corn growers rely on a less well-known triazine herbicide that is chemically very similar, but not quite identical, to atrazine.

DOI 10.1179/2049396713Y.0000000054

Syngenta's latest economic analyses of atrazine avoid the embarrassing mistakes of its earlier report. However do the new pro-atrazine studies prove their case? This article describes and critically evaluates the ABT papers, finding that they overlook potentially promising alternatives to atrazine, and fail to recognize that their own analysis implies that corn growers would be financially better off if atrazine were banned.

The ABT Papers: A Summary

Syngenta's ABT of researchers released five papers in November 2011, making a series of interrelated arguments about the benefits of and need for the continued use of atrazine in the United States. The papers, and their main points, are as follows:

- Richard Fawcett describes a decline in atrazine concentrations in surface water, despite continuing widespread atrazine usage.[11] Fawcett attributes this to adoption of best management practices, including increased use of conservation tillage and no-till systems, and other improvements in planting practices and herbicide application.
- Michael Owen asserts that atrazine is needed for weed management because so many weeds are developing resistance to other herbicides.[12] Glyphosate (Roundup) resistance is becoming particularly problematic owing to overuse of and often exclusive reliance on glyphosate with genetically modified, "Roundup ready" crops. Owen only briefly mentions atrazine resistance, which he views as a less serious threat.
- David Bridges calculates yield losses under a range of assumptions about alternate herbicide treatments.[13] Bridges examines replacement of atrazine with a single treatment, and with combinations of two or three treatments (i.e., use of a sequence of two or three herbicide applications, a common practice). Only the single-treatment results are reported in detail, although he mentions that the average yield loss from all of the two-treatment alternatives is only 2%. Almost nothing is said about the results of the three-treatment combinations. Bridges also calculates some economic impacts, assuming single-treatment replacements for atrazine and fixed prices for crops, including US$3.75 per bushel for field corn.
- Paul Mitchell's first paper applies the yield losses from Bridges' single-treatment alternatives to field corn, sweet corn, and sorghum, along with selected growers' personal judgments about likely sugarcane yield losses.[10] This paper, like Bridges, assumes fixed prices for crops, including US$3.75 per bushel for field corn. Under these assumptions, the estimated value of atrazine is US$3.0–3.3 billion per year, of which US$2.4–2.6 billion comes from increased yields in field corn.
- Mitchell's second paper develops detailed estimates of soil erosion impacts, assuming that atrazine allows greater use of no-till and conservation tillage systems.[14] The monetary value assigned to these soil erosion impacts, however, is less than 10% of the total benefit attributed to atrazine. The paper also applies the AGSIM model to estimate the overall economic impacts of atrazine use on 10 major crops, including induced changes in prices and acreage.

Mitchell's second paper is the only one of the ABT papers to analyze the crop price impacts resulting from alternative herbicide choices and crop yield changes. It is also the only one of the papers to measure the economic benefit of atrazine in terms of changes in "consumer surplus" – i.e., the benefits to consumers of lower crop prices. Although estimates are developed for all 10 crops in the analysis, corn accounts for 96% of the total consumer surplus created by the use of atrazine. However, it describes the "consumers" who enjoy the benefit of lower corn prices as primarily industries, not households: "Among end users, the benefits of triazine herbicides mostly flow to those using large amounts of corn – the livestock and ethanol industries."

There are two major problems with the ABT papers. First, they exaggerate of the effectiveness of atrazine, and offer an incomplete analysis of alternatives. Owen understates the importance of atrazine-resistant weeds, a growing problem.[12] Bridges provides only a poorly explained and partially documented account of the alternatives he analyzed.[13] Some of the chemical alternatives that score best in weed suppression are overlooked, as is the entire area of non-chemical approaches to weed management.

Second, the ABT fails to notice that, according to their own analyses, corn growers lose money from atrazine. Two of the three ABT papers looking at economic impacts of atrazine implausibly assume that crop prices are not affected by changes in crop yields and production.[10,13] The one ABT paper that allows crop prices to vary provides separate estimates of changes in crop prices and production, but never multiplies the two to calculate the implied bottom-line effect on farm revenues from atrazine use.[14] According to that paper, as we will demonstrate, the use of atrazine decreases corn growers' revenues by US$1.7 billion annually.

The following sections explain these problems in greater detail, culminating in estimates of the impacts of atrazine on consumer prices – which turn out to be quite small.

Atrazine-Resistant Weeds

Atrazine is used to control weeds, including many of those most damaging to corn crops. Nationally, approximately 70% of the potential corn yield loss owing to weed pressure is caused by only 10 weeds (see Table 1), of which all but foxtails can be classified as broadleaf weeds.[§]

Atrazine has long been employed as an herbicide to combat many of these weeds, although its effectiveness depends on the particular weed type and the extent (if any) of atrazine resistance. Owen describes

[§] Weed pressure data derived from Bridges' data on infestation and yield reduction, Tables 2 and 8.[13]

Table 1 Weed pressure in corn

Rank	Weed	Potential loss from unchecked weed growth (millions of bushels)	Approximate area infested (millions of acres)	Resistance to atrazine found in the US
1	Foxtails	3477	61	Yes
2	Pigweeds (amaranths other than Palmer amaranth)	2564	47	Yes
3	Common/Tall waterhemp	2305	46	Yes
4	Common lambsquarters	1901	38	Yes
5	Velvetleaf	1694	35	Yes
6	Other ragweeds	1538	21	No
7	Giant ragweed	1496	18	No
8	Palmer pigweed (*Amaranthus palmeri*, also called "Palmer amaranth")	1194	19	Yes
9	Cockleburs	1119	22	No
10	Morningglories	1118	27	No

Sources: Refs. 13 and 15.**

the growing resistance of weeds to glyphosate and other herbicides as a reason why atrazine is needed – and suggests in passing, with very limited documentation, that resistance to atrazine is much less important.[12] Recent empirical evidence, however, points to an expanding problem of atrazine resistance in weeds. Virtually unknown 40 years ago, atrazine resistance has spread over the years, and is now known to occur in more than 20 weed species in the United States.[15] As shown in Table 1, atrazine resistance occurs in 6 of the 10 weeds that create the greatest pressure on corn.

Owen's own recent work suggests, contrary to his ABT paper, that atrazine-resistant weeds are becoming a challenge for corn growers. In the *2013 Herbicide Guide for Iowa Corn and Soybean Production*, Owen and a coauthor report on the initial results of an analysis of weeds from more than 220 fields across Iowa, finding that among populations of common waterhemp, the third-most noxious corn weed in the United States, 57% had developed resistance to atrazine.[16] While atrazine-resistant weeds are not problematic in all regions, their increasing prevalence heightens the need to shift away from triazine herbicides to other methods of weed management, including non-chemical methods.

Alternative Herbicides

Other herbicides, such as Sharpen (saflufenacil), Callisto (mesotrione), and Equip (foramsulfuron+iodosulfuron), have been developed as alternatives to atrazine. When used in appropriate combinations (depending on the field-specific weed pressure), these alternative herbicides may offer equivalent or superior protection to atrazine, as indicated by the effectiveness ratings in Iowa State University's *2013 Herbicide Guide*, reported in Tables 2 and 3.[16] These efficacy ratings challenge the assertion by Bridges that use of alternative herbicides would necessarily result in significant yield losses.[13]

Table 2 displays the effectiveness of alternative pre-emergence herbicides (applied before the crop emerges from the ground) relative to atrazine for the weed species that are most threatening to corn yields in the United States.[††] All three of the alternative pre-emergence herbicides – saflufenacil, mesotrione, and flumetsulam+clopyralid – demonstrate significant weed control abilities against the major weeds facing corn growers. Saflufenacil and mesotrione in particular offer the added benefit of having modes of action that remain effective against weeds with resistance to atrazine, glyphosate, and ALS inhibitors.

Table 3 displays similar information for four alternative post-emergence herbicides. These herbicides, working alone or in combination, offer an alternative to atrazine with similar or potentially greater protection value.

In evaluating the effectiveness of atrazine, Bridges failed to assess mesotrione and flumetsulam+clopyralid as pre-emergence herbicides, although he evaluated them as post-emergence herbicides.[13] Two of the post-emergence herbicide treatments identified in Table 3, foramsulfuron+iodosulfuron and imazethapyr, are entirely absent from Bridges' assessment. In addition, Bridges' estimates of the average yield reduction due to atrazine alternatives were based on herbicide market share in 2009, and thus are likely skewed by the recent arrival of saflufenacil. A relatively new herbicide, saflufenacil was first registered in the

** Acreage infested is derived from Bridges' estimates of the percentage of crop acres containing a population of the weed, which, if left uncontrolled, would be sufficient to result in yield reduction. This percentage, for each agricultural region, was multiplied by the region's total acres of corn to arrive at an approximate number of acres infested. The potential bushel loss was calculated from Bridges' estimates of the average percent yield loss expected to occur in infested acreage if the specified weed was left uncontrolled, multiplied by the region's average yield per acre and number of infested acres.

†† Some species, such as pigweeds and waterhemp, are combined under their shared genus. Morningglories were not included owing to omission in the source document.

Table 2 Effectiveness ratings: alternative pre-emergence herbicides relative to atrazine[‡‡]

Herbicide	Trade name	Foxtail	*Amaranthus spp* (pigweeds and waterhemp)	Lambsquarters	Velvetleaf	Common ragweed	Giant ragweed	Cocklebur	Herbicide site of action	Chemical family
Atrazine (for comparison)		2	4	4	3	4	2.5	3	Photosystem II inhibitor	Triazine
Saflufenacil	Sharpen	1	3.5	3.5	3.5	3	3	3	PPO inhibitor	Pyrimidinedione
Mesotrione	Callisto	1	3.5	4	4	2.5	2	2.5	HPPD inhibitor	Triketone
Flumetsulam +clopyralid	Hornet WDG	1	3.5	3	3	3	3	3	ALS inhibitor; synthetic auxin	Triazolopyrimidine sulfonanilides; pyridinecarboxylic acid

Effectiveness ratings: 1=poor, 2=fair, 3=good, 4=excellent.
Sources: Refs. 16 and 17.

United States in 2009.[18] As a result, this highly effective herbicide was likely to have been nearly ignored in Bridges' calculations.

Moreover, the yield loss estimates from Bridges that are used throughout the ABT economic calculations are based entirely on a one-for-one substitution of a single alternative herbicide treatment for atrazine.[13] Bridges assesses, but does not report in detail, the results of multiple herbicide treatments to replace atrazine. He does report that 41 treatments with two herbicides in sequence[***] resulted in an average "protection value" (revenue per acre) only 2% lower than the atrazine treatments. The range of results is not disclosed, so it is unclear whether some of the 41 treatments actually resulted in protection values greater than that of atrazine.

In contrast, Prato and Woo found that non-atrazine herbicides applied in a pre- and post-emergence sequence were typically as profitable or more profitable for farmers than atrazine.[19] They analyzed northern Missouri corn production using WeedSOFT, a widely used and field-tested bioeconomic model that simulates alternative weed management practices and produces net returns.[†††] The study evaluated hundreds of herbicide treatment combinations across nine different weed pressure scenarios involving the 10 most common weed species in Missouri,[‡‡‡] and subsequently ranked each herbicide treatment by profitability. Prato and Woo found that in eight of the nine weed pressure scenarios, a two-pass system, consisting of a pre-emergence herbicide followed by a post-emergence herbicide, yielded the highest profits. Atrazine was included in only 20% of the numerous profitable two-pass treatments.[§§§] And crucially, in each of the nine weed pressure scenarios, the most profitable treatment did not include atrazine at all.

Considerable uncertainty still remains about the toxicity of these alternatives. In many cases, these

[‡‡] Table data are for weeds in Iowa, the top corn-producing state, but the effectiveness of these herbicides is likely to be similar for other corn-producing states. Atrazine entries in the table assume no resistance to atrazine, which is a questionable assumption for foxtails, pigweeds and waterhemp, lambsquarters, and velvetleaf.

[***] Two herbicides applied at the same time, such as flumetsulam and clopyralid in Tables 2 and 3, are counted as one treatment in this discussion, in contrast to sequential applications of herbicides.

[†††] WeedSOFT was developed by weed scientists and is widely used in the Midwest. Several peer-reviewed articles have evaluated the accuracy of WeedSOFT's predictions based on pooled data from numerous site-years and found that observed and predicted corn yield-loss values were similar.[20,21]

[‡‡‡] These weed species include most of the ten worst corn weed species nationally. The weed species analyzed were fall panicum, giant foxtail, common cocklebur, common ragweed, common sunflower, ALS resistant waterhemp, giant ragweed, hemp dogbane, pitted morningglory, and velvetleaf.

[§§§] Prato and Woo identified 70 different profitable two-pass treatments, 25 profitable post-emergence-only treatments, and 17 profitable pre-emergence-only treatments.[19] Atrazine was present in the majority of profitable pre-emergence-only treatments, but these were uniformly less profitable for farmers than post-emergence-only and two-pass treatments.

Table 3 Effectiveness ratings: alternative post-emergence herbicides relative to atrazine[§§]

Herbicide	Trade name	Foxtail	*Amaranthus spp* (pigweeds and waterhemp)	Lambsquarters	Velvetleaf	Common ragweed	Giant ragweed	Cocklebur	Herbicide site of action	Chemical family
Atrazine (for comparison)		2	4	4	4	4	3	4	Photosystem II inhibitor	Triazine
Foramsulfuron +iodosulfuron	Equip	3.5	3	3	3.5	4	3	4	ALS inhibitor	Sulfonylurea
Flumetsulam+clopyralid	Hornet WDG	1	3.5	2	3.5	4	3.5	4	ALS inhibitor	Triazolopyrimidine sulfonanilides; pyridinecarboxylic acid
Mesotrione	Callisto	1	4	3	4	2	3	3.5	HPPD inhibitor	Triketone
Imazethapyr	Pursuit	2.5	2.5	3	3.5	3	2	3.5	ALS inhibitor	Imidazolinone

Effectiveness ratings: 1=poor, 2=fair, 3=good, 4=excellent.
Sources: Refs. 16 and 17.

alternatives are relatively new, and thus it may take decades for the full extent of their health and environmental impacts to become apparent. The safest option would be to employ other forms of weed management techniques, as described in the following section. However, the existence of highly effective herbicide alternatives serves to highlight the fact that atrazine is not uniquely necessary for weed control.

Integrated Weed Management (IWM)

Overreliance on a few chemicals to control weeds, particularly on chemicals such as atrazine with a single herbicidal mode of action, has created a situation favoring the emergence and proliferation of herbicide-resistant weeds. Multiple factors, including the spread of resistance to both glyphosate and atrazine, the desire to reduce chemical costs, and concerns about health and ecosystem impacts of the herbicides, have led many producers to consider low-chemical or no-chemical IWM strategies.

Integrated weed management focuses not on the complete elimination of weeds, but rather on preventing weed reproduction, reducing weed emergence after crop planting, and reducing weed competition with the crop.[22] Like integrated pest management, IWM employs multiple non-chemical techniques for weed prevention and management, which may include crop rotation, intercropping, enhancements to crop competitiveness, use of cover crops, and improvements in tillage and cultivation techniques.

Tillage, for example, was historically a primary means of weed management. In the past, tillage typically meant use of the traditional mold-board plow or other conventional techniques that disturb a large amount of soil and remove the majority of crop residue, leading to high levels of erosion. Among the ABT analyses, both Fawcett and Mitchell assume that one of the benefits of atrazine use is the reduction in tillage requirements.[11,14] However, reduced-tillage methods such as ridge tillage result in little erosion while sustaining high crop yields and avoiding the use of herbicides.

Ridge tillage is designed to reduce soil disturbance; to that end, crops are planted in ridges built during cultivation in the previous growing season. The top of each ridge is pushed aside at planting, moving a large portion of residue and weed seeds to the middle of the row. Inter-row cultivation can then be used to manage weeds between the crop rows. Ridge tillage has proven to be very effective against weeds and ideal for managing water and soil erosion, as it

[§§] Table data are for weeds in Iowa, the top corn-producing state, but the effectiveness of these herbicides is likely to be similar for other corn-producing states. Atrazine entries in the table assume no resistance to atrazine, which is a questionable assumption for foxtails, pigweeds and waterhemp, lambsquarters, and velvetleaf.

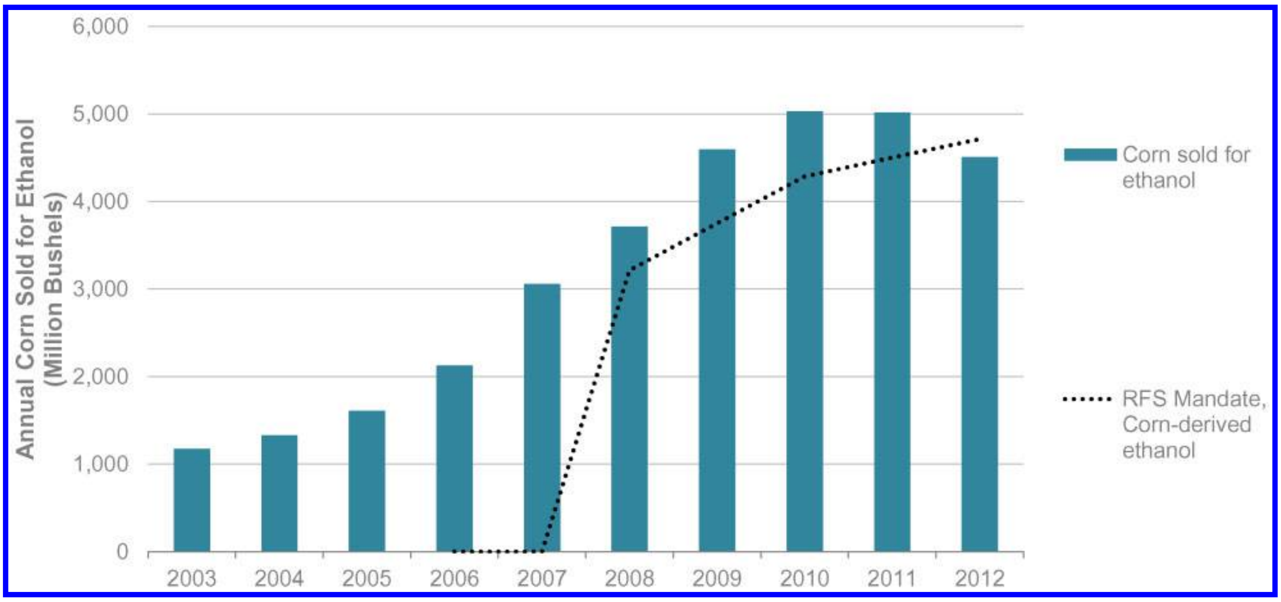

Figure 1 Corn sold for ethanol versus Renewable Fuel Standard (RFS)-mandated corn-derived ethanol, 2003–2012. Sources: Refs. 32 and 33.

encourages water infiltration and decreases runoff, resulting in higher soil organic matter and enhanced yields.[23] A long-term study at a USDA research station in Iowa demonstrated that ridge tillage increased corn yields by nearly 4% over conventional tillage.[24] Ridge tillage is an economically viable alternative to conventional tillage, as it can reduce fuel, labor, and equipment costs.[25,26]

Another similarly targeted technique is banded fertilizer placement. Application of fertilizers in narrow bands near the crop's roots, rather than broadcast over the entire field, allows the crop to absorb nutrients while denying weeds the same opportunity, and can reduce the use of chemicals.[27]

Changes in the timing of weed management can also be beneficial. Too often, effective weed management is assumed to mean eliminating 100% of weeds. However, total control is not as important as minimizing weed competition with young corn.[28] Weed competition can be manipulated through the timing of crop planting, and through weed management methods, either chemical or mechanical, during periods when the crop is particularly sensitive to weed pressure. Mechanical cultivation can be scheduled to maximize the destruction of weeds, thereby enhancing yields and profits.[29,30]

These and other effective alternative weed management practices imply that agricultural systems can reduce or even avoid reliance on chemical herbicides. Combined use of multiple IWM techniques has been shown to have a synergistic effect on weed suppression, using a multi-pronged approach that offers an effective and sustainable method of crop production without the harmful side-effects of toxic chemicals.[31] Yet the ABT analyses failed to consider these established and practical alternatives.

The Economics of Corn

As we have seen, there are multiple reasons to believe that the ABT analyses have overstated the yield losses that would occur if atrazine were withdrawn. We now turn to a different issue: even if the ABT estimates of yield impacts were completely accurate, withdrawal of atrazine from the market would substantially boost corn growers' incomes, while the effects on consumer prices would be merely pennies per pound of beef or gallon of gasoline. Explanation of this point requires a brief look at the market for corn in the United States.

Total corn production doubled from 1975 to its all-time peak of 13 billion bushels in 2009.[****] Average annual production over the past 10 years has been about 11.8 billion bushels, with a slump to 11.2 billion bushels in 2012 likely due to that year's extensive drought.[††††] In 2012, ethanol accounted for 40% of the corn market, and animal feed another 37%; the remainder consisted of exports and other domestic uses.[32]

The rapidly rising demand for ethanol, which accounted for only 10% of corn sales as recently as 2002, has paralleled the EPA's Renewable Fuel Standard (RFS), which requires high levels of ethanol production. Originally a part of the Energy Policy Act of 2005 and updated with the Energy Independence and Security Act of 2007, the RFS requires the use of minimum volumes of a variety of biofuels, including ethanol.

Biofuel requirements have proved controversial in at least two respects: there are disagreements about

[****] Corn production data cited here are all for market years; e.g., 2009 means September 2008–August 2009.

[††††] See http://www.ers.usda.gov/topics/in-the-news/us-drought-2012-farm-and-food-impacts.aspx.

Table 4 Price elasticities of demand for corn

Author	Womack	Subotnick and Houck	Gallagher	Wescott and Hoffman	Park and Fortenbery
Study Year	*1976*	*1982*	*1994*	*1999*	*2007*
Corn price elasticity (general)			−0.23	−0.3 to −0.5	
Corn price elasticity for feed	−0.4	−0.2			
Corn price elasticity for food	−0.08	−0.014			
Corn price elasticity for exports		−1.11			
Corn price elasticity for ethanol					−0.16

Source: Ref. 37.

whether they achieve significant greenhouse gas reductions when produced by fossil fuel-intensive agriculture; and there is little doubt that they have exerted upward pressure on food prices, contributing to food insecurity in low-income countries and regions. Nonetheless, biofuel mandates and subsidies are an important part of the contemporary market for corn, and for motor fuel. Figure 1 compares the corn used for ethanol to the requirements of the RFS (converted from gallons to bushels) for 2003 through 2012.[‡‡‡‡]

The surge in demand has led to a sharp rise in the price of corn, which was almost US$7 per bushel in 2012, more than US$4 above the level in 2005 (prices in 2011 US$).[34] The timing suggests that this price increase was largely driven by the ethanol mandate. In comparison, the ABT analysis projects that corn prices would increase by only US$0.30 per bushel due to a shift away from atrazine.[14]

Costs of corn production have risen in recent years, although not as rapidly as corn prices. In order to keep increasing production, growers may have had to plant corn on more marginal or expensive land. Agricultural chemicals are not the cause of cost increases; they account for only a modest cost per acre. In 2010, chemicals made up 9% of the costs of producing corn, and atrazine represented less than 13% of the total cost of chemicals, or about 1% of the overall cost of producing corn.[34–36] Thus an alternative that costs a few times as much per acre as atrazine would add only a few percent to corn production costs.

Price Elasticity and Revenues

When the price of corn – or almost anything else – changes, the amount that is purchased will typically change as well. Economists measure the impact of price changes by the ''price elasticity of demand'' – the percent change in quantity purchased that is associated with a 1% increase in price, assuming no change in any other factors that affect sales. Table 4 presents the range of published price elasticities of demand for corn. As expected, all are negative – that is, demand goes down when price goes up. However, they are very small negative numbers; with the exception of one estimate for corn exports, all the elasticity estimates are less than or equal to 0.5.[§§§§]

When the price elasticity for a good is less than 1, demand for that good is referred to as ''inelastic,'' meaning that it is relatively unresponsive to price. A 1% increase in price causes a decrease of less than 1% in the quantity that is purchased. Conversely, a 1% reduction in quantity would be associated with an increase of more than 1% in price. For example, with a price elasticity of −0.5, a 1% decrease in the quantity supplied would be associated with a price increase of 2%.

The consensus in the literature that the price elasticity for corn (aside from exports) is much less than 1 is not surprising. Food, feed, and fuel, the principal uses of corn, all face inelastic demand. The inelastic demand for corn, however, is the key to an important but unadvertised result: according to Mitchell, the only one of the ABT analysts to analyze price changes, eliminating atrazine would significantly increase farm revenues.[14]

Mitchell models impacts on 10 crops of two no-atrazine scenarios, one that maintains constant intensity of glyphosate use, and one that increases glyphosate use above 2009 levels.[14] Compared to the baseline with atrazine, the no-atrazine, constant-glyphosate scenario would decrease corn production by 4.4%, but would increase the price of corn by 8.0% (see appendix). Similar results occur in the increased glyphosate scenario. Mitchell's modeling implies a price elasticity for corn of approximately −0.55, around the high end of the estimates from the literature.[*****]

The combination of Mitchell's estimated 4.4% decrease in production and 8.0% increase in price leads to a 3.2% increase in revenues for corn growers from the withdrawal of atrazine. As shown in the appendix, this implies a gain of US$1.7 billion for corn growers under 2009 conditions with constant

‡‡‡‡ RFS mandate data from Ref.33; bushels of corn converted to gallons at 2.8 gallons of ethanol per bushel. Corn for ethanol data from Ref.32.

§§§§ We follow common usage in referring to elasticities with smaller absolute values as ''smaller''; e.g., ''less than 1'' is understood to mean ''less than 1 in absolute value'' when discussing elasticities.

***** The implied price elasticity is the ratio of these percentage changes: $-4.4/8.0=-0.55$.

glyphosate use.[†††††] This important result has to be calculated from Mitchell's separate production and price estimates; it is never reported in the paper.

The key to this result is the fact that the decrease in corn production occurs nationwide. If a single farmer grows 4.4% less but no one else's yield changes, then the price is likely to be unchanged and the unlucky farmer suffers a 4.4 loss of sales revenue. However, if everyone produces 4.4% less, then prices rise by more than enough to offset the reduction in output, leaving all farmers with increased revenue.

Two other ABT papers, Bridges and the earlier paper by Mitchell,[10,13] emphasize the decrease in farm revenues that would be caused by the withdrawal of atrazine under the implausible assumption that corn yields would decline but corn prices would not change.[‡‡‡‡‡] Yet the more sophisticated economic modeling of Mitchell's second paper, allowing prices to change, leads only to evaluation with a different measure of economic benefit, the "consumer surplus" created by atrazine.[14] While corn growers would be better off without atrazine, corn buyers – primarily the ethanol and livestock industries – would be worse off.

In short, according to the ABT's best modeling effort, the benefit of atrazine is that it allows lower corn prices, making corn growers worse off so that corn-using industries can benefit from cheaper purchases. Consumer goods, however, are only very slightly cheaper as a result. The impacts on consumers – the value to the public of the "consumer surplus" created by atrazine – turn out to be surprisingly small, as explained in the next section.

Corn Without Atrazine: Who Wins and Who Loses?

Mitchell's projection that loss of atrazine would cause an 8% jump in the price of corn is undoubtedly too extreme. The ABT analyses overlooked many of the most attractive alternatives to atrazine, including the newest and most promising chemical alternatives and the wide range of non-chemical techniques for managing weeds and increasing yields. Pursuing these alternatives will be important in order to address the growing threat of atrazine resistance and to continue the development of non-toxic, sustainable agricultural techniques. With these alternatives, the reduction in corn output caused by the elimination of atrazine should be less than the ABT's projected 4.4%, and the price increase and other economic impacts should be correspondingly muted.

Suppose, however, that the ABT analysis is exactly right, and elimination of atrazine would result in the production of 4.4% less corn. The winners in an atrazine-free future would include farmworkers, farmers and their families, and others who are exposed to atrazine either directly from field uses or indirectly from contaminated tap water, along with the natural ecosystems that are currently damaged by atrazine.

The nation's corn growers would also be winners in narrowly economic terms: their revenues would, according to the ABT analysis, be US$1.7 billion greater without atrazine. Elimination of atrazine would lead to both a reduction of 4.4% in corn production and an 8.0% increase in corn prices, leaving farmers better off financially.

The losers include the buyers of corn, primarily the ethanol and livestock industries. Paying 8% more for corn, these industries would have to raise their own prices, switch to other inputs, and/or reduce their own production. What would happen if the producers of ethanol and beef, the top corn-using industries, passed on an 8% increase in the price of corn to consumers?

The scope, if not the existence, of the ethanol industry is heavily dependent on federal and state policies that mandate or support ethanol use. Once touted as a sustainable biomass alternative to petroleum products, corn-based ethanol has become increasingly controversial. Some environmental analysts now find that greenhouse gas emissions from the production of corn ethanol may be almost as great as the emissions from the equivalent petroleum-based fuels.[38] Thus losses or contraction in the ethanol industry may not be setbacks for the environment.

If ethanol producers had to pay 8% more for corn, they would either produce less (if reductions are allowed by government policy) or raise their own prices. The price of corn is not the only cost of ethanol production; thus an 8% increase in corn prices should mean less than an 8% increase in ethanol costs. Consider, however, a worst-case scenario in which ethanol prices go up by 8%. Since ethanol is only a fraction of the fuel delivered to motor vehicles, the price rise at the gas pumps would be much smaller than 8%.

In 2011, ethanol made up 9% of the volume of gasoline consumed in the United States; the amounts vary by region, but in general do not exceed 10% by volume.[§§§§§] If ethanol makes up 10% of the fuel used by automobiles, then an 8% increase in the price of ethanol means a 0.8% increase in overall fuel price

[†††††] The $1.7 billion revenue gain to corn growers is partially offset by small revenue decreases in other crops, and by decreased payments under the Conservation Reserve Program (CRP), as some CRP land is pulled into corn production by the higher corn price. The gains in corn revenues, however, are much larger than these offsetting reductions. There is still a net increase of $1.4 billion in farm revenues from all ten crops combined (see appendix) plus CRP payments. (The decline in CRP payments, not shown in the appendix, is less than $50 million.) Similar but somewhat smaller results occur in Mitchell's scenario in which glyphosate use increases.

[‡‡‡‡‡] In technical terms, this would imply infinite price elasticity, since a non-zero percent change in quantity would be associated with a zero change in price.

[§§§§§] US Energy Information Administration, "Frequently Asked Questions," http://www.eia.gov/tools/faqs/faq.cfm?id=27&t=4, accessed 2 April 2013.

Table A1 Farm revenues with and without atrazine

Crop	Prices (Ref. 14, Table 24), US$			Production (Ref. 14, Table 26)			Farm revenues (million 2009 US$)		
		No-atrazine scenarios			No-atrazine scenarios			No-atrazine scenarios	
	Baseline with atrazine	Constant glyphosate	Increasing glyphosate	Baseline with atrazine	Constant glyphosate	Increasing glyphosate	Baseline with atrazine	Constant glyphosate	Increasing glyphosate
Barley	3.95	3.97	3.97	248	247	247	980	981	981
Corn	3.75	4.05	3.99	14 505	13 862	13 975	54 394	56 141	55 760
Cotton	0.64	0.63	0.63	18 255	18 278	18 292	5608	5527	5532
Hay	120.55	120.42	120.42	159	159	159	19 167	19 147	19 147
Oats	2.35	2.37	2.37	101	100	100	237	237	237
Peanuts	0.23	0.23	0.23	4558	4549	4556	1048	1046	1048
Rice	11.78	11.74	11.71	236	236	237	2780	2771	2775
Sorghum	3.35	4.01	3.98	405	297	296	1357	1191	1178
Soybeans	8.80	8.79	8.80	3259	3263	3261	28 679	28 682	28 697
Wheat	5.45	5.44	5.43	2301	2304	2305	12 540	12 534	12 516
						Total	126 791	128 256	127 870

Units for prices vary by crop (e.g. price per bushel for corn); in all but one case, production is in millions of the corresponding units.
For cotton, Mitchell reports prices per pound but mislabels them as prices per 480-pound bale; production is in thousand bales.
Mitchell presents three variants of each no-atrazine scenario, using differing tillage assumptions. Data shown here are for the moderate tillage assumption; results for the other assumptions are quite similar.

(assuming no change in the costs of the other 90% of fuel). At US$4.00 per gallon, this would mean a fuel price increase of only US$0.03 per gallon.

For the beef industry, corn is a major cost of production, but far from the only cost. A detailed academic study implies that a 1% increase in the price of corn leads to only a 0.165% increase in beef prices.****** A similar result is reached by a different, simpler route, which estimates the impacts if beef producers pass on the cost of corn price increases to the final consumers. Such an analysis implies that a 1% increase in the price of corn would cause a 0.174% rise in beef prices.†††††† Both of these studies imply that a 1% increase in the price of corn causes about a 0.17% rise in the price of beef – that is, corn price changes are about six times as large as beef price changes. The true impact could be even lower: another recent study finds, unexpectedly, that in the years since the adoption of the federal ethanol mandate (during which corn prices have risen significantly, as discussed above), short-run changes in corn prices have had no impact on beef prices.[41]

To estimate the impact of an atrazine ban on consumers, assume that a 1% increase in corn prices implies a 0.17% increase in beef prices. Mitchell's projection that an atrazine ban would cause an 8% increase in corn prices then translates into a 1.4% increase in the retail price of beef. Ground beef would increase from an average of US$3.81 per pound‡‡‡‡‡‡ to US$3.86; the cost of a 4-ounce hamburger would rise by just over US$0.01. Top-quality sirloin would rise from an average of US$7.08 per pound to US$7.18; the cost of an 8-ounce entrée at a steak-house would jump up by US$0.05 (plus tax and tip). These price impacts appear to be too small to cause a noticeable change in beef consumption.

In short, the elimination of atrazine would improve human health and the natural environment in farming regions; prompt the development of more sustainable, less toxic agricultural practices; increase farm revenues; and have impacts on consumer prices measured in pennies. So where's the beef?

Appendix 1: Revenues with and without atrazine

Table A1 provides the data behind the calculation, discussed in the text, that farm revenues from the sale

****** Marsh finds that a 1% increase in corn prices is associated with a 0.28% decrease in the quantity of cattle slaughtered, and that a 1% increase in cattle slaughtered is associated with a 0.59% decrease in the price of cattle.[39] The effect of a 1% increase in corn prices on cattle prices is thus equal to $(-0.28)\times(-0.59)=0.165$.

†††††† Leibtag calculates that a 50% jump in corn prices would raise beef prices by 8.7%, implying a beef price increase of $(8.7/50)=0.174\%$ per percentage point increase in corn prices.[40] His estimates of impacts on other corn-based foods are even smaller.

‡‡‡‡‡‡ February 2013 US city average, all uncooked ground beef, from US Bureau of Labor Statistics, http://www.bls.gov/ro3/apmw.htm, accessed 1 April 2013.

of corn would be higher without atrazine. All data and assumptions are taken directly from Ref. 14 (Tables 24 and 26).

Conflict of Interest

The authors have declared no conflict of interest.

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