The Benefits of Chlorine Chemistry in Crop Protection

PREPARED FOR:

Chlorine Chemistry Council

PREPARED BY:

GLOBAL INSIGHT

24 Hartwell Avenue
Lexington, MA 02421-3158

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The Benefits of Chlorine Chemistry in Crop Protection Chemicals

The agricultural sectors of the economies in the United States and Canada are very large, amounting to over $230 billion in 2004, or about 2.4% of the gross domestic product of both countries. Although crop protection chemicals account for only a small fraction of the input to the farm economies, they are a critical input to improve productivity and yield and reduce soil erosion. Farm level expenditures on crop protection chemicals in 2004 amounted to less than $10 billion. This amount excludes expenditures by homeowners for lawn and garden care and other uses (e.g. golf courses). For purposes of this analysis, crop protection chemicals include herbicides, insecticides, fungicides, nematicides, and growth regulators.

The costs of the other components of the farm economy far exceeded the cost of crop protection chemicals, yet the use of these materials, together with natural and synthetic fertilizers, improve crop yields, reduce crop losses, reduce soil erosion and produce higher quality agricultural products. Without effective and safe crop protection chemicals, farmers would incur significant costs to maintain the current high level of agricultural production, and consumers would pay much higher prices for the agricultural products.

For consumers of agricultural products in the United States and Canada, the economic benefits of chlorine chemistry can be measured as the difference in the total cost that would be incurred in the absence of chlorine-based products compared with their current cost. For this analysis, we have evaluated the composition and manufacturing processes for the top-selling 133 crop protection products. These products represent more than 90% of the total sales of herbicides, insecticides, fungicides, nematicides, and growth regulators sold in the United States in 2004. Chlorine chemistry is widely used in the production of these crop protection products. More than 48% of these products contain chlorine on the molecule. Over 38% of them use chlorine chemistry in the manufacturing process – chlorine-containing intermediates, for example, which lose their identity during the course of building up the molecule from smaller constituents. Thus, chlorine chemistry is implicated in the manufacture of more than 86% of the top-selling crop protection products – less than 14% do not have chlorine implicated at all and they represent only 10% of the sales volume of all crop protection chemicals.

For United States and Canadian consumers, the net economic benefit of chlorine chemistry in crop protection products is estimated to of the order of $15 billion per year. At this level, the benefits amount to about 1.7 times the cost of the affected crop protection products. This analysis validates previous research on the economic importance of chlorine chemistry in this sector and suggests that chlorine chemistry will continue to provide substantial benefits to the farm economy and consumers in general well into the future. The benefits are extremely large relative to the amount and value of the chlorine that is consumed to produce them.
Introduction

Crop protection chemicals include compounds that are used as herbicides, insecticides, fungicides, nematicides, and growth regulators and for other purposes in agriculture. Farmers use these materials, together with natural and synthetic fertilizers, to improve yields, reduce crop losses, reduce soil erosion and produce high-quality products at the lowest possible cost to consumers. Farm level expenditures on crop protection chemicals were approximately $8.5 billion in the United States in 2004, and are estimated to be about $1.3 billion in Canada. While these materials are used on almost all commercial crops, about three quarters of the sales are for chemicals that are applied to the economically important ones, including corn, soybeans, cotton, potatoes, rice, wheat, sugar beets, apples, almonds and pasturage.

Over the past decade the types and amounts of crop pesticides has changed dramatically, particularly in the United States. The adoption of genetically modified seed or transgenic crops has been the dominant force in this change. In the case of soybean herbicides, the use of Roundup-ready technology (plants genetically modified to be resistant to the herbicide glyphosate) has nearly eliminated the use of other herbicide products. A similar revolution occurred in the area of insecticides on cotton and to a lesser extent corn. The ability to modify plants so they will create their own Bacillus thuringiensis toxin has dramatically reduced the application of conventional insecticides such as organophosphates, pyrethroids, and carbamates on cotton. These technologies can be stacked such that corn weeds can be controlled by glyphosate herbicides and insecticide use can be reduced or eliminated.

These crop protection solutions using genetically modified organisms (GMO) have been well-received by farmers. Over the past ten years, adoption of GMO crops has moved from zero to 85% for soybeans, 76% for cotton, and 45% for corn. These adoption rates have continued to increase during 2005 and 2006.

The use of chemical pest control measures has declined in recent years primarily due to increased use of genetically modified seed and increased production of organic food. For example, organic food production has seen significant penetration in the baby food market. Overall organic farming practices represent a very small portion of total production with certified organic crop area increasing from 0.55 million acres in 1994 to 1.45 million in 2003. Relative to total crop area, however, the 2003 level represents less than 0.5% of farmland.

Pesticides are also sold to homeowners for yard and garden application. The benefits these products provide to homeowners are improved aesthetics and reduced weeds and pests, while minimizing the labor that otherwise would have to be devoted to such chores. For this analysis, however, we will calculate the economic benefits of chlorine-based crop protection chemicals solely to the agricultural sector of the United States and Canada, conservatively assuming that the benefits derived by homeowners are much

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1 See United States Department of Agriculture, Economic Research Service and Statistics Canada.
smaller because the sales into this sector are much lower and homeowners can substitute “free” labor for the chemicals they might otherwise purchase.

<table>
<thead>
<tr>
<th>Type of Crop Protection Chemical and Commodity</th>
<th>1964</th>
<th>1971</th>
<th>1982</th>
<th>1991</th>
<th>1997</th>
<th>2004</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Use</td>
<td>215.0</td>
<td>364.4</td>
<td>572.4</td>
<td>477.5</td>
<td>579.3</td>
<td>494.5</td>
</tr>
<tr>
<td>Use by Function</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Herbicides</td>
<td>48.2</td>
<td>175.7</td>
<td>430.3</td>
<td>335.2</td>
<td>362.6</td>
<td>311.0</td>
</tr>
<tr>
<td>Insecticides</td>
<td>123.3</td>
<td>127.7</td>
<td>82.7</td>
<td>52.8</td>
<td>60.2</td>
<td>40.7</td>
</tr>
<tr>
<td>Fungicides</td>
<td>22.2</td>
<td>29.3</td>
<td>25.2</td>
<td>29.4</td>
<td>48.5</td>
<td>29.8</td>
</tr>
<tr>
<td>Other</td>
<td>21.4</td>
<td>31.7</td>
<td>34.2</td>
<td>60.1</td>
<td>108.0</td>
<td>112.9</td>
</tr>
<tr>
<td>Use by Commodity</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Corn</td>
<td>41.2</td>
<td>127.0</td>
<td>273.7</td>
<td>233.2</td>
<td>227.3</td>
<td>174.6</td>
</tr>
<tr>
<td>Cotton</td>
<td>95.3</td>
<td>111.9</td>
<td>49.5</td>
<td>50.3</td>
<td>68.4</td>
<td>56.7</td>
</tr>
<tr>
<td>Wheat</td>
<td>10.1</td>
<td>13.6</td>
<td>23.5</td>
<td>13.8</td>
<td>25.5</td>
<td>22.3</td>
</tr>
<tr>
<td>Soybeans</td>
<td>9.2</td>
<td>42.2</td>
<td>147.4</td>
<td>70.4</td>
<td>83.5</td>
<td>87.8</td>
</tr>
<tr>
<td>Potatoes</td>
<td>6.1</td>
<td>15.5</td>
<td>24.6</td>
<td>35.6</td>
<td>59.4</td>
<td>62.1</td>
</tr>
<tr>
<td>Other vegetables</td>
<td>20.8</td>
<td>20.7</td>
<td>21.7</td>
<td>40.3</td>
<td>73.3</td>
<td>65.1</td>
</tr>
<tr>
<td>Citrus fruit</td>
<td>8.1</td>
<td>14.1</td>
<td>16.5</td>
<td>13.7</td>
<td>15.0</td>
<td>7.2</td>
</tr>
<tr>
<td>Apples</td>
<td>19.9</td>
<td>12.7</td>
<td>10.0</td>
<td>9.1</td>
<td>10.6</td>
<td>8.5</td>
</tr>
<tr>
<td>Other deciduous fruit</td>
<td>4.4</td>
<td>6.6</td>
<td>5.5</td>
<td>11.1</td>
<td>16.4</td>
<td>10.3</td>
</tr>
</tbody>
</table>


The agricultural sectors of the economies in the United States and Canada are very large, amounting to about $233 billion in 2004 or about 2.4% of their combined gross domestic product. Although crop protection chemicals account for only a fraction of the input to the farm economies, they are a critical input to improve productivity and yield. It has been estimated, for example, that the use of herbicides on 40 crops provides farmers in the United States benefits of about 3.2 dollars for every dollar spent on crop protection. It is also known that chlorine chemistry is heavily involved in the manufacture of crop

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3 L. P. Gianessi, op. cit.
protection chemicals, and that the agricultural economy, and ultimately all consumers, would incur significant costs if they were deprived of access to them.\textsuperscript{4}

In this analysis we are seeking to quantify the benefits that the use of chlorine chemistry brings to the consumers of crop protection chemicals in the United States and Canada today. We will do this by estimating the impacts on the farm economies that would result from the absence of chlorine-based crop protection chemicals. The methodology used to quantify the benefits and the results of this analysis are presented in the following sections.

**Benefits Estimation Methodology**

For consumers of crop protection chemicals, the economic benefit of chlorine chemistry can be measured as the difference in the total cost that would be incurred in the absence of chlorine-based products compared with their currently cost. Because the application of crop protection chemicals is a distributive use, and because some of them are toxic and persistent in the environment, their use has been subject to strict regulatory regimes for many years. While the use of some compounds has been banned and others subject to curtailments or phase-outs in North America, they continue in widespread use because they provide economic benefits vis-à-vis use of available alternatives.

Previous research has shown that the majority of crop protection chemicals in use had chlorine covalently bound to the molecule, and that most of the remainder had chlorine chemistry implicated in their manufacture.\textsuperscript{5} Many of these chemicals have been in use for more than 30 years. While new, improved products with smaller environmental footprints have been developed as substitutes for some of these products, the involvement of chlorine chemistry has not necessarily decreased significantly. Thus, it is not realistic to assume that alternative, economically viable chlorine-free chemistries can be developed generally to substitute for the majority of the crop protection chemicals currently in use. If these products were no longer available, farmers would have recourse to other alternatives, including:

- **GMO Option:** Farmers could choose to grow only crops that have been genetically engineered to be resistant to pests or to tolerate chlorine-free crop protection chemicals. This option has some obvious risks since limiting the types of chemical control products across several crops to a single or relative few has in some cases resulted in resistant pests (weeds, insects, and funguses). Excessive use of these types of GMO solutions thus has the potential to make them ineffective. This alternative represents an extension of current practice beyond economically demonstrated limits, since many important crops are already genetically engineered. More widespread use of genetically engineered crops is a controversial issue in its own right, however, and there is no assurance that such approaches would be economically viable in the smaller, more fragmented sectors of the agricultural economy.


\textsuperscript{5} Charles River Associates, op. cit.
"Do Without" Option: Farmers could choose to increase tillage, use hand cultivation and inspection techniques, and use synthetic chemical-free methods of pest control. Increased tillage would be an alternative to use of herbicides, but probably would result in yield losses and certainly would result in higher soil erosion than would be the case with reduced or no-till agriculture. Increased hand cultivation and inspection is also possible, although at a dramatically higher cost, and the cost and effectiveness of widespread use of “natural” means of pest control is not clear.

Option to Employ Other Agricultural Resources More Intensively: Farmers could put more land into cultivation and increase their use of irrigation, fuels and mechanical means to plant, grow and harvest the crops that would be produced at lower yield in the absence of currently used chlorine-based crop protection chemicals. Since yield losses must be expected if crop protection chemicals are not available, land of lower quality than currently in use will have to be brought under cultivation, and such land will be more expensive to farm.

All of these alternatives are in use today to varying degrees throughout the agricultural economy, including the “organic farming” sector. It is generally recognized that crops grown without the use of synthetic crop protection chemicals are more costly to produce than those that use them. This is partly a result of the economies of scale typically enjoyed by users of crop protection chemicals, but is due mainly to the more efficient use of the inputs throughout the rest of the agricultural sector. Users of herbicides with vegetable crops may spend about $50 per acre on weed control, for example, while organic farmers may spend $1,000 per acre and suffer significant yield reductions. In general, any decrease in the range of crop protection chemicals available to farmers will force them to rely more heavily on less efficient components of agricultural input, and this will increase costs in the sector and to consumers.

The net increase in the costs that would be incurred, which is the benefits to consumers of the access to chlorine-based crop protection chemicals, can be estimated through the use of an appropriate model of agricultural economics. The Cobb-Douglas model, described in more detail in Appendix A, can be used to estimate the impacts of changes in any of the inputs to the agricultural sector to changes in its output. In this case, we assume that farmers would strive to maintain their current economic status, passing any increases in costs through to the consumer. Then we seek to estimate the extent to which the other inputs to the agricultural economy would have to increase to offset the losses resulting from farmers’ inability to use the full range crop protection chemicals.

To use the Cobb-Douglas model in this manner we need to know the current distribution of costs for crop protection chemicals and for all other inputs to the agricultural sector, and the extent to which the costs of crop protection chemicals would change if chlorine chemistry were not available. The estimated current distribution of costs in the United States and Canadian agriculture sectors is summarized in Table 2.

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6 L. P. Gianessi, op. cit.
The involvement of chlorine chemistry in the manufacture of crop protection chemicals is described in the next section.

**Chlorine Chemistry in the Manufacture of Crop Protection Chemicals**

Information on the sales of crop protection chemicals used on more than 60 crops in the United States was obtained for 2004. Over three hundred chemical entities were identified in the crop protection category, and they were categorized by their use as herbicides, insecticides, fungicides, nematicides or growth regulation chemicals. Some compounds in the list can have application in more than one category. To focus on the most economically important entities, we selected the compounds that account for the top 90% of the sales in each category for more detailed investigation. This subset amounted to 133 entities.

The chemical composition of each entity was determined, and this permitted immediate identification of those compounds that contained chlorine covalently bound to the structure or present as the chloride, bromide or hydrochloride salt. It also permitted the identification of some compounds for which chlorine is not implicated in their manufacture, such as the fungicides copper, copper hydroxide, copper sulfate, sulfur and petroleum oil. About 48% of the sampled compounds were found to contain chlorine in their structure and only 14% were found to be demonstrably chlorine-free. For the remaining compounds, the patent literature and other sources were consulted to determine if chlorine was involved in their manufacture.

Many of these entities are complex, heterocyclic organic compounds that contain one or more of the elements bromine, fluorine, nitrogen, oxygen, sulfur, phosphorous, manganese, zinc or tin in their structures. Bromine contained on the molecule or in the synthesis of a compound implicates chlorine, since bromine is produced commercially

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7 Global Insight, Inc., US Agriculture Service.
8 A major resource for this information is www.alanwood.net.
9 Patent information can be found at www.uspto.gov.
from bromine-rich brines using chlorine gas. They are often synthesized using techniques well known to organic chemists, which involve the use of chlorine-containing intermediates even though chlorine itself does not appear in the structure of the final compound. The manufacturing processes also may use solvents, including chlorinated solvents, at various steps in the process to dissolve solids or to separate and purify them and use HCl for control of pH. Of the remaining compounds surveyed, 39% were found to have chlorine involved in their manufacture and only 2% were found to have been synthesized without the involvement of chlorine chemistry.

The involvement of chlorine chemistry in the production of the crop protection chemicals sampled sold in the United States in 2004 is summarized in Table 3.

<table>
<thead>
<tr>
<th>Type of Product</th>
<th>Sales in Category, $Million</th>
<th>Cl/Br on Molecule</th>
<th>Chlorine in Manufacture</th>
<th>No Chlorine Involvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Herbicides</td>
<td>4,285</td>
<td>52.0</td>
<td>42.0</td>
<td>6.0</td>
</tr>
<tr>
<td>Insecticides</td>
<td>1,293</td>
<td>38.9</td>
<td>47.2</td>
<td>13.9</td>
</tr>
<tr>
<td>Fungicides</td>
<td>623</td>
<td>53.6</td>
<td>21.4</td>
<td>25.0</td>
</tr>
<tr>
<td>Nematicides</td>
<td>225</td>
<td>33.3</td>
<td>50.0</td>
<td>16.7</td>
</tr>
<tr>
<td>Growth Regulators</td>
<td>280</td>
<td>46.2</td>
<td>38.5</td>
<td>15.4</td>
</tr>
<tr>
<td>Total, All Categories</td>
<td>$6,706</td>
<td>48.8</td>
<td>41.2</td>
<td>10.0</td>
</tr>
</tbody>
</table>

Source: Global Insight, Inc.
Note: Totals may not add to 100% due to rounding.

In our sample across the five different crop protection categories, the lowest level of chlorine involvement is in the manufacture fungicides (75%), and the highest level of chlorine involvement is in the manufacture of herbicides (94%). In the other categories, chlorine is implicated in the manufacture of nearly 85% of the products. Overall, the current distribution of sales of these products shows about 6% less involvement with chlorine on the molecule than was found in a previous study of this sector. These changes reflect a gradual shift away from the consumption of the older, heavily chlorinated, persistent products and increased use of genetically engineered crops and more careful application techniques to reduce environmental impacts.

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10 Charles River Associates, op. cit.
We evaluated the top-selling 133 crop protection products to obtain the information shown in Table 3. Sales of these products represent at least 90% of total U.S. sales in each category in 2004. Since the total involvement of chlorine chemistry in these compounds is high in all categories, and is the same order of magnitude as the sample evaluated in 1993, we assume that these results are representative of the involvement of chlorine chemistry in the sales of all crop protection products sold in the United States and in Canada.

Examples of chlorine-involvement of the top fifteen crop protection chemicals are shown in Table 4.

### Table 4
Chlorine Chemistry in the Manufacture of the 15 Top-Selling Crop Protection Chemicals in 2004

<table>
<thead>
<tr>
<th>Crop Protection Product</th>
<th>Sales ($Million)</th>
<th>Primarily Used for the Management of</th>
<th>Cl/Br on Molecule</th>
<th>Chlorine in Manufacture</th>
<th>No Chlorine Involvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glyphosate</td>
<td>$1,240.6</td>
<td>Weed control</td>
<td>Yes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Metolachlor-S</td>
<td>307.6</td>
<td>Weed control</td>
<td>Yes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acetochlor</td>
<td>296.9</td>
<td>Weed control</td>
<td>Yes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Atrazine</td>
<td>206.5</td>
<td>Weed control</td>
<td>Yes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mesotrione</td>
<td>137.9</td>
<td>Weed control</td>
<td>Yes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Imidacloprid</td>
<td>113.3</td>
<td>Insects</td>
<td>Yes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2,4-D</td>
<td>96.5</td>
<td>Weed control</td>
<td>Yes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aldicarb</td>
<td>92.2</td>
<td>Insects</td>
<td>Yes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nicosulfuron</td>
<td>91.5</td>
<td>Weed control</td>
<td>Yes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clothianidin</td>
<td>91.4</td>
<td>Insects</td>
<td>Yes</td>
<td></td>
<td></td>
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<tr>
<td>Chlorpyrifos</td>
<td>84.1</td>
<td>Insects</td>
<td>Yes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tebuirimphos</td>
<td>79.1</td>
<td>Insects</td>
<td>Yes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mepiquat</td>
<td>76.1</td>
<td>Growth regulator</td>
<td>Yes</td>
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<td></td>
</tr>
<tr>
<td>Azoxyystrobin</td>
<td>76.0</td>
<td>Fungicide</td>
<td>Yes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ethephon</td>
<td>75.7</td>
<td>Growth regulator</td>
<td>Yes</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Source: Global Insight, Inc.

The Benefits of Chlorine Chemistry in Crop Protection Chemicals

If we assume that only 10% of crop protection products currently available (i.e., those with no involvement in chlorine chemistry), would remain available to farmers, we can apply the Cobb-Douglas model to predict that the net cost to consumers in the United States and Canada would increase by almost $15 billion per year. This is about 1.7 times the cost of the crop protection products assumed to be no longer available. Almost $13 billion of the benefits accrue to consumers in the United States while $2 billion accrue to Canadian consumers, in both cases with a ratio of benefits to costs of about 1.7. This multiplier is at the lower end of the range estimated by other researchers of the direct economic benefits of crop protection products.\(^\text{11}\)

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\(^{11}\) Charles River Associates, op. cit., estimated this ratio to be 4x and L. P Gianessi, op. cit., estimated the ratio for total non-use of herbicides to be 3.2x.
The Cobb Douglas model is useful for estimating how farmers could employ other factors of production like agricultural land, farm equipment, farm labor, and fertilizers in order to maintain their current level of farm production and income, but does not identify specifically how the necessary changes would occur. A “bottom-up” analysis would have to be carried out to determine the specific trade-offs that would have to be made for each crop. That type of analysis has been done, however, to determine the cost impacts of banning herbicide use on selected crops in the United States.12

If we focus on the impacts of chlorine chemistry on herbicides alone, the Cobb Douglas model predicts that the benefits to consumers in the United States are almost $11 billion per year, which is 2.1 times the cost of the compounds consumed. These benefits do not arise from a complete avoidance of herbicide use since six percent of those currently available do not involve chlorine in their manufacture. If we assume that nearly all herbicides were no longer available (say only 1% remained), the Cobb Douglas model would predict that costs to consumers would increase to about $21 billion, which is four times the cost of the herbicides currently used. These values for total costs and the ratio of benefits to costs are quite consistent with the bottoms-up analyses of the costs avoided through use of herbicides, and confirm the validity of the approach taken in this analysis.

Summary of the Benefits of Chlorine Chemistry

Although crop protection chemicals account for only a small fraction of the input to the farm economies, they are a critical input to improve productivity and yield and reduce soil erosion. Farm level expenditures on crop protection chemicals in 2004 amounted to less than $10 billion. This amount excludes expenditures by homeowners for lawn and garden care and other uses (e.g. golf courses). Chlorine chemistry is involved in the manufacture of 90% of the crop protection chemicals currently sold in the United States and Canada. This chemistry is involved extensively in the production of insecticides, fungicides, nematicides, and growth regulators.

The costs of the other components of the farm economy far exceeded the cost of crop protection chemicals, yet the use of these materials, together with natural and synthetic fertilizers, improve crop yields, reduce crop losses, reduce soil erosion and produce higher quality agricultural products. Without effective and safe crop protection chemicals, farmers would incur significant costs to maintain the current high level of agricultural production, and consumers would pay much higher prices for the agricultural products.

For consumers of agricultural products in the United States and Canada, the economic benefits of chlorine chemistry can be measured as the difference in the total cost that would be incurred in the absence of chlorine-based products compared with their current cost. For this analysis, we have evaluated the composition and manufacturing processes for the top-selling 133 crop protection products. These products represent more than 90% of the total sales of herbicides, insecticides, fungicides, nematicides, and growth regulators sold in the United States in 2004. Chlorine chemistry is widely used in the production of these crop protection products. More than 48% of these products contain chlorine on the molecule.

12 L. P. Gianessi, op. cit.
Over 38% of them use chlorine chemistry in the manufacturing process – chlorine-containing intermediates, for example, which lose their identity during the course of building up the molecule from smaller constituents. Thus, chlorine chemistry is implicated in the manufacture of more than 86% of the top-selling crop protection products – less than 14% do not have chlorine implicated at all and they represent only 10% of the sales volume of all crop protection chemicals.

For United States and Canadian consumers, the net economic benefit of chlorine chemistry in crop protection products is estimated to of the order of $15 billion per year. At this level, the benefits amount to about 1.7 times the cost of the affected crop protection products. This analysis validates previous research on the economic importance of chlorine chemistry in this sector and suggests that chlorine chemistry will continue to provide substantial benefits to the farm economy and consumers in general well into the future. The benefits are extremely large relative to the amount and value of the chlorine that is consumed to produce them – less than five percent of total chlorine consumption in the United States and Canada.
Taking a closer look

Every year, U.S. growers choose herbicides as the primary method to kill weeds that would otherwise significantly lower yields. An average U.S. cropland acre is treated with two pounds of herbicide active ingredient costing $30 per acre. The widespread use of herbicides is crops growth throughout the United States has resulted in yield increases, savings for growers and reduced soil erosion.

**Economics:** The nonuse of herbicides with likely substitution of alternatives would result in $13.3 billion loss in food and fiber production, or a decline of approximately 21 percent of national production.

**Labor requirements:** As a major replacement of herbicides for many crops, hand weeding requirements would increase by 1.2 billion hours. These high labor levels would still be inadequate to control all weeds, and yield losses would result.

**Soil erosion:** Erosion of cropland has been reduced significantly over the past 70 years, largely as a result of reducing tillage. Without herbicide use, no-till agriculture becomes impossible, resulting in increased erosion. Much of this soil erosion would enter the waterways and significantly reduce the quality of the nation’s surface water.

Appendix A*

Cobb-Douglas Economic Model

The Cobb-Douglas economic model seeks to understand how various combinations of inputs (or factors of production) can be combined to produce goods and services in the economy. In a simple three-factor model, the production function can take on the following general form:

\[ Q = f(K, L, M) \]

where \( Q \) represents the quantity of output of a particular industry, \( K \) represents the amount of capital employed in the industry, \( L \) represents the hours of labor input, and \( M \) represents the quantity of raw materials consumed. The functional form, \( f \), represents the technological relationships used to convert the various inputs into final products or services. In more complex situations, there may be other variables as well.

The form of this model suggests that decision makers can choose different combinations of the various factors of production to achieve different levels of output. For instance, if the cost of labor rises dramatically, then capital might be substituted for labor to achieve a particular level of output. The trade-offs between factor inputs and different levels of output define the shape and key characteristics of the production process.

For practical purposes, economists have conducted numerous empirical studies of actual production relationships in a wide variety of industries using various types of production functions. At the aggregate level, these models provide useful insight regarding the interrelationships between different combinations of inputs and the level of output.

Mathematically, we used a special case of this class of economic models defined below:

\[ Q = A K^a L^b M^c \]

where \( A, a, b, \) and \( c \) are all positive constants. When \( a + b + c = 1 \), the Cobb-Douglas function exhibits two useful and interesting properties: constant returns to scale and constant elasticity of substitution. Constant returns to scale means that doubling all factors of production will result in a doubling of output. The elasticity of substitution is a measure of how easy or difficult it is to substitute one input for another.

In a simple example, suppose there are only two factors of production, labor (\( L \)) and capital equipment (\( K \)). The trade-off between these two factors of production in a Cobb-Douglas function can be depicted in Exhibit A-1 as a set of isoquant curves, where an isoquant curve is defined as the alternative combinations of productive inputs that can be used to produce a given level of output. The different levels of output are represented by the contour lines \( Q_1, Q_2, \) and \( Q_3 \).

* This section has been adapted from the authors’ previous research at Charles River Associates, op. cit.
In Global Insight’s production function model for pharmaceutical products, we assume that the coefficients $a$, $b$, and $c$ can be defined as the expenditure share of each factor input $K$, $L$, and $M$. This is equivalent to assuming constant elasticity of substitution among the factors of production, and we calculate:

\[
a = \frac{K}{K + L + M}
\]

\[
b = \frac{L}{K + L + M}
\]

\[
c = \frac{M}{K + L + M}
\]

If we assume that pharmaceutical products based on chlorine chemistry are no longer available (see text for alternative assumptions), we solve this mathematical model to estimate how much the other factors of production would have to increase in order to compensate for the loss of the chlorine-based products.

**Exhibit A-1**

Cobb-Douglas Production Function Isoquants