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The Benefits of Chlorine Chemistry in Crop Protection in the United States and Canada

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Executive summary

The agricultural sectors in the United States and Canada are very large, amounting to over $517 billion in 2014, or about 2.7% of the combined gross domestic product of both countries. Although crop protection products account for only a small fraction of the input to farm economies, they are a critical input to improve productivity and yield and reduce soil erosion. Farm level expenditures for both countries on crop protection products in 2014 amounted to approximately $18 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 products include herbicides, insecticides, fungicides, nematicides, and growth regulators.

The costs of other components of the farm economy far exceeded the cost of crop protection products, 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 products, farmers would incur significant costs to maintain the current high level of agricultural production, and consumers would pay much higher prices for 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 more than 100 of top-selling 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 2014. Chlorine chemistry is widely used in the production of these crop protection products. Fifty percent (50%) of these products contain chlorine on the molecule. Another thirty-nine percent (39%) 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 involved in the manufacture 89% of the top-selling crop protection products – only 11% are not associated with chlorine at all.

For United States and Canadian consumers, the net economic benefit of chlorine chemistry in crop protection products is estimated to be roughly $26 billion per year. The net economic benefit for US consumers is $22.9 billion and for Canadian consumers it is $3.1 billion. At this level, the benefits amount to about 1.6 times the cost of the affected crop protection products. The benefits are extremely large relative to the amount and value of the chlorine that is consumed to produce them. 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 well into the future.

Introduction

Crop protection products include compounds that are used as herbicides, insecticides, fungicides, nematicides, 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 products were approximately $15.8 billion in the United States in 2014, and are estimated to be about $2.5 billion in Canada.[1] 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 crops, 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 considerably, particularly in the United States. The adoption of genetically modified seed or transgenic crops is the main reason for this change. By 2014, roughly 95% of corn, soybeans, and cotton acres were planted with genetically modified seeds with combined traits to help with the control of insects and weeds. Generally speaking, the insecticidal traits caused reduced use of conventional chemicals, while the herbicide resistant technology has caused reductions and switching from a broad range of products to a more focused set including glyphosate and more recently 2,4-D – both of which are based on chlorine chemistry.[2]

Crop protection solutions using genetically modified organisms (GMO) have been well-received by farmers. The addition or stacking of 2,4-D with glyphosate will allow farmers to continue using the technology despite the development of several weeds that are resistant to glyphosate. The trend toward organic food production continues to forge ahead, but the pace has slowed from the rapid growth over a decade ago. A newer movement that could impact the use of crop protection products in the future is the pursuit of non-GMO foods.

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 with minimized labor that otherwise would have to be devoted to such chores. For this analysis, however, we calculate the economic benefits of chlorine-based crop protection products solely to the agricultural sector of the United States and Canada, conservatively assuming that the benefits derived by homeowners are much smaller because the sales into this sector are much lower and homeowners can substitute "free" labor for the chemicals they might otherwise purchase.

1 For the United States, http://www.ers.usda.gov/data-products/farm-income-and-wealth-statistics/data-files-us-and-state-level-farm-income-and-wealth-statistics.aspx; for Canada: http://www5.statcan.gc.ca/cansim/a26?lang=eng&retrLang=eng&id=0020005&tabMode=dataTable&srchLan=-1&p1=-1&p2=9

2 The chemical name is 2,4-dichlorophenoxyacetic acid.

Quantity of crop protection product applied in the United States
(millions of pounds active ingredient)

	1964	1971	1982	1991	1997	2004	2014
Total use							
	215.0	364.4	572.4	477.5	579.3	494.5	493.0
Use by crop protection product							
Herbicides	48.2	175.7	430.3	335.2	362.6	311.0	296.6
Insecticides	123.3	127.7	82.7	52.8	60.2	40.7	35.7
Fungicides	22.2	29.3	25.2	29.4	48.5	29.8	41.5
Other	21.4	31.7	34.2	60.1	108.0	112.9	119.2
Use by commodity							
Corn	41.2	127.0	273.7	233.2	227.3	174.6	170.3
Cotton	95.3	111.9	49.5	50.3	68.4	56.7	41.9
Wheat	10.1	13.6	23.5	13.8	25.5	22.3	24.4
Soybeans	9.2	42.2	147.4	70.4	83.5	87.8	101.6
Potatoes	6.1	15.5	24.6	35.6	59.4	62.1	64.1
Other vegetables	20.8	20.7	21.7	40.3	73.3	65.1	63.1
Citrus fruit	8.1	14.1	16.5	13.7	15.0	7.2	5.8
Apples	19.9	12.7	10.0	9.1	10.6	8.5	8.1
Other deciduous fruit	4.4	6.6	5.5	11.1	16.4	10.3	13.6
Total use	**215.0**	**364.4**	**572.4**	**477.5**	**579.3**	**494.5**	**493.0**

Note: Sum may not add to total due to rounding.

Source: US Department of Agriculture, Economic Research Service, and US Census Bureau

The agricultural sectors of the United States and Canada are very large, amounting to about $517 billion in 2014 or about 2.7% of their combined gross domestic product.[3] Although crop protection products 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.[4] It is also known that chlorine chemistry is heavily involved in the manufacture of crop protection products, and that the agricultural economy, and ultimately all consumers, would incur significant costs if they were deprived of access to them.[5]

In this analysis we are seeking to quantify the benefits that the use of chlorine chemistry brings to the consumers of crop protection products in the United States and Canada. We will do this by estimating the impacts on the farm economies that would result from the absence of chlorine-based crop protection products. 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 products, 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 current cost. Because the application of crop protection products is a distributive use, and because some of them are considered to be toxic and persistent in the environment, their use has been subject to strict regulatory regimes for many years.

3 IHS, Inc., *US Agriculture Executive Summary*, November 2015 and IHS, Inc., *Canadian Agriculture Forecast*, November 2015.

4 L. P. Gianessi and N. Reigner, *The Value of Herbicides in U.S. Crop Production*, CropLife Foundation, 2006.

5 *Assessment of the Economic Benefits of Chlor-Alkali Chemicals to the United States and Canadian Economies,* Charles River Associates, April, 1993.

Previous research has shown that the majority of crop protection products in use had chlorine covalently bound to the molecule, and that most of the remainder had chlorine chemistry involved in their manufacture.[6] Many of these products have been in use for more than 40 years. While new products 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 products 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 products. This option has some 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 fungi). 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, and there is no assurance that such approaches would be economically viable in the smaller, more fragmented sectors of the agricultural economy.

- **"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 the 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 a lower yield in the absence of currently used chlorine-based crop protection products. Since yield losses must be expected if crop protection products are not available, land of lower quality than currently in use would have to be brought under cultivation, and such land would be more expensive to farm.

All of these alternatives are in use today to varying degrees throughout the agricultural economy. It is generally recognized that crops grown without the use of synthetic crop protection products are costlier to produce than those that use them. This is partly a result of the economies of scale typically enjoyed by users of crop protection products, but is mainly due to the more efficient use of the inputs throughout the rest of the agricultural sector. Users of herbicides in 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.[7] In general, any decrease in the range of crop protection products available to farmers will force them to rely more heavily on less efficient components of agricultural input, thus increasing costs in the sector and to consumers.

The net increase in the costs that would be incurred, which are the benefits to consumers of the access to chlorine-based crop protection products, can be estimated by using an appropriate model of the agricultural economy. 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. We then 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 of crop protection products.

6 Global Insight, *The Benefits of Chlorine Chemistry in Crop Protection*, 2006.

7 L. P. Gianessi, op. cit.

To use the Cobb-Douglas model in this manner we need to know the current distribution of costs for both crop protection products and all other inputs to the agricultural sector, and the extent to which the costs of crop protection products 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 the table.

The involvement of chlorine chemistry in the manufacture of crop protection products is described in the next section.

Estimated expenditures in agriculture sector, 2014
($ billion)

	United States	Canada	Total
Crop protection products	15.8	2.5	18.3
All Other Inputs	386.5	50.2	436.7
Total costs	**401.4**	**52.7**	**454.1**

Note: All cost data are expressed in current US dollars. Canadian costs are converted to US dollars using the average exchange rate for 2014 (US$/C$ = .909).

Source: US Agriculture Service and IHS

Chlorine chemistry in the manufacture of crop protection products

Information on the sales of crop protection products used on more than 60 crops in the United States was obtained for 2014.[8] Over one 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 chemicals, we selected the compounds that accounted for the top 90% or more of the volume in each category for a more detailed investigation. This subset amounted to 28 different chemicals.

The chemical composition of each entity was determined, which permitted immediate identification of those compounds that contained chlorine covalently bound to the structure or present as the chloride or hydrochloride salt.[9] Bromine products were also similarly identified because the industrial production of bromine involves the direct reaction of chlorine with brine rich in bromine ions. The process occurs in two stages – the oxidation of bromide ions with chlorine followed by the purification of bromine.[10] It also permitted the identification of some compounds for which chlorine is not involved in their manufacture, such as the copper hydroxide, copper sulfate, sulfur and petroleum oil. Fifty percent (50%) of the sampled compounds were found to contain chlorine in their structure.

For the remaining compounds, the patent literature and other sources were consulted to determine if chlorine was involved in their manufacture.[11] 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. 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. Thirty-nine percent (39%) of the compounds were found to have chlorine involved in their manufacture and not present on the final product; eleven percent (11%) of the compounds did not involve chlorine chemistry.

8 IHS, Inc., US Agriculture Service.

9 A major resource for this information is www.alanwood.net.

10 Since bromine is found on the molecule of a very small number of crop protection products, we will henceforth consider bromine and chlorine as equivalent chemistries.

11 Patent information can be found at www.uspto.gov.

The involvement of chlorine chemistry in the production of the crop protection products sold in the United States in 2014 is summarized in the table below.

Chlorine chemistry in the manufacture of crop protection products

Product	Sales in category, $ million	Percent of total sales with: Cl on molecule	Chlorine in manufacture	No chlorine involvement
Herbicides	6,620	54	40	6
Insecticides	2,110	44	47	9
Fungicides	1,822	50	20	30
Nematicides	570	33	50	17
Growth regulators	709	48	39	14
	Total Sales		**Weighted average value**	
All products	**11,831**	**50**	**39**	**11**

Note: Percent total across products may not add to 100% due to rounding.

Source: IHS

In our sample across five different crop protection categories, the lowest level of chlorine involvement was in the manufacture of fungicides (70%), and the highest level of chlorine involvement was in the manufacture of herbicides (94%). In the other categories, chlorine is involved in the manufacture of 83% to 91% of the products. Relative to earlier research of this sector, the current distribution of sales of these products shows that there has been little change in the use of products where chlorine appears on the molecule.

We evaluated the most heavily used crop protection products to obtain the information shown in Table 3. Consumption of these products represented at least 90% of total US consumption in each category in 2014. Since the total involvement of chlorine chemistry in manufacture of these compounds is high in all categories, and is roughly the same order of magnitude as the samples evaluated in 2006, we assume that these results are representative of the involvement of chlorine chemistry in the production of all crop protection products sold in the United States and Canada. Examples of chlorine-involvement in the manufacture of the top fifteen crop protection products are shown in the table below..

Chlorine chemistry in the manufacture of the 15 most heavily used crop protection products, 2014

	Primarily used for the management of	Cl on molecule	Chlorine in manufacture	No chlorine involvement
Glyphosate	Weed control		Yes	
Atrazine	Weed control	Yes		
Metam-Sodium	Insects		Yes	
S-Metalachlor	Weed control	Yes		
Acetochlor	Weed control	Yes		
Sulfuric acid	Weed control			Yes
Dichloropropene	Insects	Yes		
Sulfur	Fungicide			Yes
2,4-D	Weed control	Yes		
Metam-Potassium	Insects		Yes	
Propanil	Weed control	Yes		
Chlorothalonil	Fungicide	Yes		
Pendimethanil	Weed control	Yes		
Dimethenamid	Weed control	Yes		
Mesotrione	Weed control		Yes	

Source: IHS

The benefits of chlorine chemistry in crop protection products

Assuming that only 11% of the crop protection products currently available (i.e., those that do not involve the use of chlorine chemistry) would remain available to farmers, we can apply the Cobb-Douglas model to predict the net cost to consumers in the United States and Canada. Doing so lead to the conclusion that consumer costs would increase by almost $26 billion per year. This is about 1.6 times the cost of the crop protection products assumed to be no longer available. Due to their relative sizes, over $22 billion of the benefits would accrue to consumers in the United States while $4 billion would accrue to Canadian consumers, in both cases with a ratio of benefits to costs of about 1.6. This multiplier is at the lower end of the range estimated by other researchers of the direct economic benefits of crop protection products.[12]

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 it does not identify specifically how the necessary changes would occur. A "bottoms-up" analysis would have to be carried out to determine the specific trade-offs that would have to be made for each crop to maintain current production and income.

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 and Canada are almost $13 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 6% of those herbicides currently available do not involve chlorine in their manufacture. Again, 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 products 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 products in 2014 amounted to approximately $18 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 89% of the crop protection products 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 other components of the farm economy far exceeded the cost of crop protection products, 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 products, farmers would incur significant costs to maintain the current high level of agricultural production, and consumers would pay much higher prices for 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 evaluated the composition and manufacturing processes for more than 100 top-selling 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 2014. Chlorine chemistry is widely used in the production of these crop protection products. Fifty percent (50%) of these products contain chlorine on the molecule. Another 39% 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 involved in the manufacture of 89% of the top-selling crop protection products. Only 11% of the crop protection products are not associated with chlorine at all.

12 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.

For United States and Canadian consumers, the net economic benefit of chlorine chemistry in crop protection products is estimated at roughly $26 billion per year. The net economic benefit for US consumers is $22.9 billion and for Canadian consumers it is $3.1 billion. At this level, the benefits amount to about 1.6 times the cost of the affected crop protection products. The benefits are extremely large relative to the amount and value of the chlorine that is consumed to produce them – crop protection products account for less than 5% of total chlorine consumption in the United States and Canada. 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.

Taking a closer look

Prior to the 20th century, insects consumed much of the nation's crops. In the early 1900s, farmers began using inorganic and botanical compounds, which greatly reduced crop losses to insects. The introduction of synthetic chemical insecticides in the 1950s revolutionized chemical control of insect pests. Newly discovered insecticidal molecules were rapidly adopted by US farmers for their expanded range of insect control and their increased effectiveness. Today, insecticides are integral to the production of crops in the United States. Their use results in increased yields and farmer income. If left untreated, insects will consume plant foliage, roots, and stems reducing yield, making crops unmarketable, and in some cases, killing the plant.

Economics: Each year, approximately 45 million acres of US crops are treated with insecticides. These insecticides cost farmers a total of $1.2 billion per year. If left untreated, most major crops would suffer nationwide production losses of 40% or greater. Insecticides enable US farmers to produce and harvest greater marketable yields than would otherwise be possible. By mitigating the effects of crop feeding insects, US farmers produced 144 billion pounds of additional food, feed, and fiber, and reaped an additional $22.9 billion in farm income.

Bottom line: For every dollar spent on insecticides, US growers gain $19 dollars in increased production value. Without the use of chlorine in crop protection products, U.S. and Canadian farmers would experience significantly lower crop yields and, with the large loss in productivity, the need for a large farm population and work force. Chlorine has helped free us from the drudgeries of farm life and lowered the cost of food for the average citizen.

Source: Excerpted from L. P. Gianessi, The Value of Insecticides in US Crop Production, March 2009, Crop Life Foundation, Washington, D.C.

Appendix A[13]

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 inter-relationships 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 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.

In IHS's production function model for the agricultural economy, 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 = K / (K + L + M)

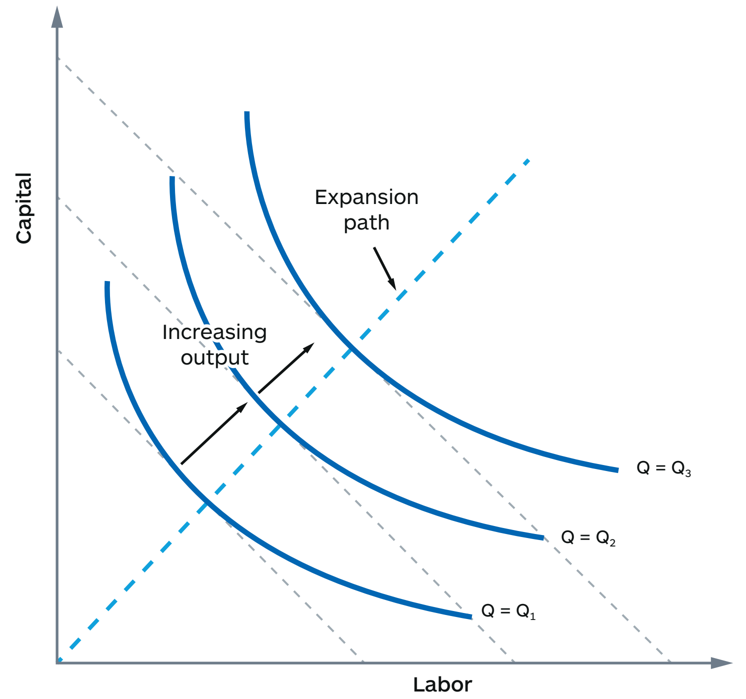
b = L / (K + L + M)

c = M / (K + L + M)

13 This section has been adapted from the authors' previous research, Global Insight, *The Benefits of Chlorine Chemistry in Crop Protection*, 2006.

If we assume that crop protection 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.

Cobb-Douglas production function isoquants



Source: IHS