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ALSO IN THIS ISSUE

The New Social Cost of Carbon

Maximilian Auffhammer

The Social Cost of Carbon is a dollar figure, which measures the damage caused from one more ton of the greenhouse gas CO_2 emitted. The federal government uses this number in benefit cost analysis to evaluate new regulations. The current administration has dropped this number from \$42 to a range of \$1–\$7. This has significant consequences for environmental policy.

Economics has been influential in the policy arena over the past century, but maybe our biggest impact has been through the insertion of benefit cost analysis into the regulatory process. When the federal government designs new policies, or contemplates the tightening or loosening of existing regulations, the implementing agencies are required to compare the benefits of the policy (change) to its cost.

This is often not straightforward to do, as putting a number on the benefits of, say, better air quality, requires knowledge of how many fewer people die from bad air, changes in soil acidity and consequential agricultural production, changes in the acidity of lakes for recreational fishing, and what the dollar value of these changes is.

On the cost side, the regulator needs to learn how much it would cost firms, who have no incentive to truthfully report this number, to reduce their emissions of air pollutants. But over the years, the government, with the help of academics, has established a number of guidelines to help us come up with estimates of costs and benefits in all types of settings.

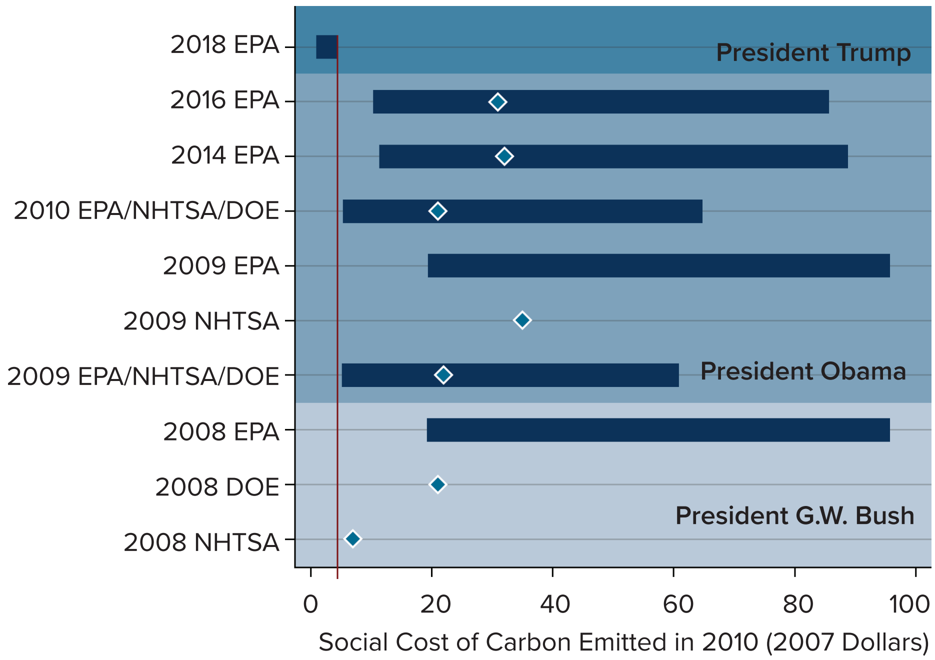
Climate change historically posed one of the toughest challenges in benefit cost analysis due to the scale of time, space and economic sectors involved. First off, carbon dioxide, the main greenhouse gas, once emitted, affects the global climate for hundreds of years. Projected changes will include changed temperature, precipitation and cloud patterns, sea-level rise, as well as the increased intensity and possibly frequency of extreme events worldwide. Second, each ton of CO_2 emitted (roughly what your car emits if you drove it from San Francisco to Chicago) will cause changes in climate everywhere on earth, hence the origin of emissions does not matter. Finally, the number of economic sectors affected by the changed climate is significant.

Extreme heat has been shown to lead to higher mortality, lower crop yields, higher electricity consumption, and increased conflict to name but a few. Hence, if you want to calculate the benefits from reducing emissions of CO_2 by one ton, you would have to calculate the damages this ton would cause over the next 300 or so years. Globally. For all economic sectors. This number is called the Social Cost of Carbon (SCC) and it is hard to calculate.

What Is the Social Cost of Carbon and How Do You Calculate It?

In order to calculate the SCC, economists have employed so called Integrated Assessment Models, which integrate simple models of the economic and climate system. These models start with assumptions about the evolution of global, and in some cases regional, income and population over the next 300 years. The models then translate economic activity into emissions of greenhouse gases (GHG), most notably CO_2, but in some cases other GHG such as methane.

Figure 1. Sample of SCC Estimates Used in Federal Rulemakings for Three Administrations



Notes:
The blue diamond indicates the "central estimate."
The blue bars indicate selected upper and lower bounds used in regulatory analyses.
Measured in 2007 dollars for a ton of emissions in 2010.
NHTSA—National Highway and Traffic Safety Administration; IWG—Interagency Working Group;
EPA—Environmental Protection Agency; DOE—Department of Energy.

Source: Auffhammer (2018)

These 300-year time paths of emissions are then fed into a climate model, which translates emissions into surface temperature, precipitation, and sea level rise. These outputs are then fed to a set of so-called damage functions, which map the emissions path into economic damages.

In order to calculate the effect higher emissions have on outcomes of interest across the many sectors of the economy, the Integrated Assessment Model is run with and without one additional ton of CO_2. The difference in damages relative to the baseline path represents the damages from that one ton for each year over the next 300 years. The stream of damages is then discounted into a present value, as future dollars are worth less than current dollars. This dollar amount is called the Social Cost of Carbon and is measured in US$.

This number represents the damages caused globally over time by one additional ton of CO_2 emissions. The SCC is higher for emissions made later in time, as they are generally understood to be more damaging due to the elevated stock of greenhouse gases in the atmosphere, and because gross domestic product (GDP) grows over time and some damage categories are modeled as proportional to GDP.

How Do We Use the SCC and How Big Is It?

The federal government has employed the Social Cost of Carbon in rulemakings since the Bush administration in 2008. Figure 1 shows a set of values used by the three last administrations. For comparability, the graphic shows values for one ton of CO_2 emitted in the year 2010 valued in 2007 US$.

Towards the end of the Bush administration, EPA used a range of $19–$96 per ton, when it examined regulating greenhouse gas emissions under the Clean Air Act. In the early years of the Obama administration, an Interagency working group (IWG) embarked on an effort to calculate an official Social Cost of Carbon, which could be used across agencies in all federal rulemaking. The approach adopted, which is described in detail in Greenstone, Kopits, and Wolverton (2013), was to feed three integrated assessment models with a set of harmonized assumptions.

The number emerging from this effort, which has since been employed in the majority of economic studies on the external costs of climate change, was $42 per ton emitted in 2020 as measured in 2007 dollars. This means that one ton of CO_2 emitted in 2020 is thought to cause $42 of damages globally. The IWG provided detailed information on the evolution of the SCC over time and for a variety of assumptions about how much value is placed on future generations as reflected by the approach used to discount future dollars.

The New "Trumpian" SCC

Under the current administration, several policy proposals have been made in the environmental arena. The most significant is the proposed rollback of President Obama's tightened fuel efficiency standards. If you read through the thousands of pages underlying the proposed rule, you will note that the Social Cost of Carbon has been slashed from $42 to $1 or $7, suggesting a massive decrease in the damages caused by the same ton of CO_2 that was modeled by the Obama team. So how did that happen? Is CO_2 not as bad as we thought? No.

The National Highway Traffic Safety Administration (NHTSA), the agency in charge of this policy proposal, did two things to arrive at this new, lower number. First, they significantly decreased the value we place on future generations by increasing the discount rates used to between 3%–7% from the 2.5%–5% the Obama administration used.

A forthcoming paper in a top economics journal surveyed experts on the subject and they arrive at a median social discount rate of 2%. The share of experts that stated that the preferred rate is lower than 3% is 67%. Meaning two-thirds of experts on the topic surveyed think the lowest rate used by the administration is too high. By increasing the discount rate, you decrease the implied damage numbers significantly.

The much bigger change is that NHTSA is using a domestic Social Cost of Carbon. This means they used the above-mentioned integrated assessment models to calculate a number for damages occurring on U.S. soil only. There are at least three reasons why the domestic number may not be fit for rulemaking.

The economically correct number is global, as the Interagency Working Group argued, since the underlying externality (think damages imposed on humans, animals, and plants) is global. Carbon dioxide does not stop causing damages at the U.S. borders. The issue here is that if each country uses only domestic damages—which are much lower—to design its optimal regulations, each country will emit an inefficiently large amount of greenhouse gases and the world gets inefficiently hot! If the U.S. starts using a domestic number, this is likely to lead other countries to do the same, which might have a domino effect.

The simplistic way in which the domestic Social Cost of Carbon was calculated is a crude approximation and leaves out important spillover effects on the United States. For example, U.S. firms own capital and rely on suppliers located abroad. The analysis ignores this. If a climate change-fueled storm takes out all of Apple's suppliers' manufacturing facilities in China, this is free to the U.S. according to this analysis. If a heatwave affects major wheat producers outside of the U.S., this has no consequences for U.S. producers in this setting. The way the number was calculated also does not take into account national security implications and important effects on trade flows and global commodity markets.

By using a domestic SCC, the analysis places zero weight on the welfare of U.S. citizens living abroad. This includes the men and women serving in the U.S. armed forces (~450,000) abroad as well as U.S. citizens (~9,000,000) living abroad. If members of the armed forces are exposed to climate change-induced events elsewhere, according to this analysis, we do not care as a society. Also, if climate change leads to more conflict, resulting in more troop deployments, this is not accounted for.

Figure 1 shows the consequences of these modeling decisions quite clearly. The range of estimates used since the Bush and throughout the Obama administration ranged between $20 and $100. The number adopted under the Trump administration is $1–$7. Is this based on good science? The answer is no.

The non-partisan National Academies of Sciences reviewed the approach taken by the Interagency Working Group and made a set of concrete suggestions to improve how the SCC is determined. NHTSA did not implement any of these updates, although many of the suggestions have already been implemented in the peer-reviewed literature and are hence readily available. The most glaring omission is the lack of updates to the antiquated damage functions, which are mathematical functions translating changes in climate into economic damages, in the integrated assessments used to calculate the SCC.

This lack of scientific rigor used in the calculation of the SCC makes policy which increases emissions look much less damaging than it actually is. Further, the administration has disbanded the Interagency Working Group and ordered all innovation on modeling the SCC to stop.

Fortunately, there are two major research efforts underway pushing the frontier of this literature. Resources for the Future (rff.org) is working on implementing the suggestions made by the National Academies of Sciences. Another joint effort between the University of Chicago, UC Berkeley, and Rutgers University (impactlab.org) is focusing on providing cutting edge, empirically based damage functions. Initial results indicate that the SCC is likely much larger than previously thought, which does not surprise this economist.

Author's Bio

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For additional information, the author recommends:

Auffhammer, Maximilian. 2018. Quantifying Economic Damages From Climate Change. *Journal of Economic Perspectives*. 32(4): 33-52

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U.S. Environmental Protection Agency/Interagency Working Group. 2016. Current Technical Support Document (2016): Technical Update to the Social Cost of Carbon for Regulatory Impact Analysis under Executive Order 12866.

Faculty Profile: Bulat Gafarov

Bulat Gafarov
Assistant Professor
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Bulat Gafarov is an assistant professor with an appointment in the Department of Agricultural and Resource Economics at UC Davis. Bulat received his Ph.D. in economics from the Pennsylvania State University in August 2017.

Bulat's recent research in econometric theory has focused on developing new methods for inference in economic models with identification failure. His dissertation was focused on improving the computational and statistical properties of confidence sets for dynamic effects of structural shocks using time service data and for linear regression models with interval-valued data.

In related work, Bulat and co-authors Matthias Meier (University of Mannheim) and José Luis Montiel Olea (Columbia University) have developed a new statistical method to quantify uncertainty in the response of a given time series (such as gross domestic product) to an unexpected disruption (such as an intervention by the Federal Reserve in the long-term treasury bond market).

The method makes it possible to quantify both uncertainties coming from the limited number of statistical observations and our ignorance about the specific instant reaction (or lack of it) of the time series to the shock. The method only assumes a direction, positive or negative, of this reaction. They use their results to assess the effects of the announcement of the Quantitative Easing program in August 2010. This research paper was published in *Journal of Econometrics*.

In current work, Bulat develops confidence sets for coefficients in a linear regression model with interval-measured outcome variable. Datasets of this kind are frequently encountered in income surveys and used, for example, to estimate effects of schooling on income. Interval measurements would typically result in interval estimates of the regression coefficients, which requires special statistical inference procedures.

It is challenging for the existing robust methods to tackle existing big datasets with a large number of control variables. Bulat proposes a new method to construct confidence sets for the effect of a regressor that is based on application of convex programming techniques. This technique enables a much bigger number of control variables to be included in the regression model.

Bulat grew up in Bashkortostan, one of the major oil-producing regions in Russia. Naturally, he was interested in natural resource markets, because it affected life around him. He is excited to start new projects with his colleagues at UC Davis and apply his technical skills to answer challenging questions in resource economics.

Bulat is currently studying an unintended impact of environmental regulations on the market power of gasoline refineries that can potentially explain the price differential between California and the rest of the US. From 2000 until the Torrance refinery fire in early 2015, the differential went up and down, but on average there was no premium above what you would expect from tax differences and those other costs. According to some expert estimates, the extra payments since the Torrance refinery fire have cost California drivers about $15 billion.

In addition to research, Bulat enjoys swimming, biking, and playing with his children.

Economic Value of the Herbicide Dacthal for Brassica and Allium Crops in California

Steven Blecker, Steven Fennimore, Rachael Goodhue, Kevi Mace, John Steggall, Daniel Tregeagle, Tor Tolhurst, and Hanlin Wei

California review of the herbicide dacthal triggered by the requirements of California's Pesticide Contamination Prevention Act was conducted in 2018. This article estimates the economic effects a cancellation of dacthal's California registration would have on brassica and allium crops. Statewide net revenue losses for broccoli, dry onion, and cabbage, the largest users of dacthal, are estimated at $25.4 million: $17.9 million for broccoli, $2.4 million for cabbage, and $5.1 million for onion.

Broccoli alone accounted for 40% of pounds of dacthal applied in 2014–2016 in California, and almost half of treated acreage.

A review of dacthal (aka chlorthal-dimethyl or DCPA) was initiated in early 2018 by the California Department of Pesticide Regulation (DPR) due to the detection of its degradates in groundwater. Under California's Pesticide Contamination Prevention Act, the confirmed detection of a pesticide active ingredient or degradation product in groundwater, which arises from legal agriculture use, automatically triggers a review. The purpose of the formal review is to determine whether or not the pesticide can continue to be used and, if so, under what conditions. One of the considerations in the review is whether or not a regulatory response would cause "severe economic hardship" for California agriculture.

This article evaluates potential economic impacts for brassica and allium crops if the California registration for dacthal was canceled. It is derived from a larger report prepared for consideration in the review process. Ultimately, DPR determined that the level of dacthal degradates was below the level of toxicological concern. If this had not been the case, economic impacts would have been considered as part of the regulatory response required to reduce pollution. Groundwater monitoring for dacthal and its degradates will continue, and DPR will continue to review new research that could alter these review findings.

Background

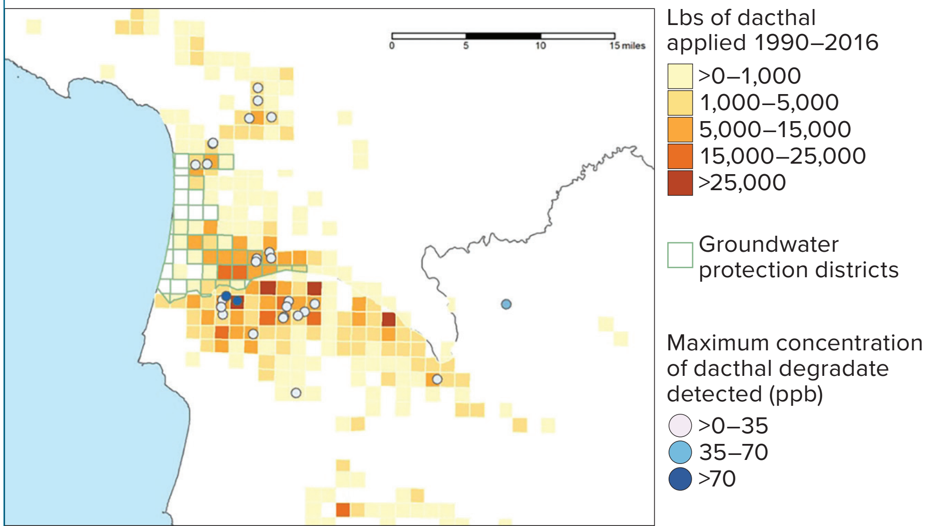
Dacthal is a selective pre-emergence herbicide used for controlling annual grasses and certain broadleaved weeds. The value of dacthal is its long list of crop registrations and excellent selectivity on a large number of crops in the allium (onion family) and brassica (mustard family) crops, which account for the majority of dacthal use. These crops have few alternative herbicides with similar selectivity and efficacy. Broccoli alone accounted for 40% of pounds applied in the 2014–2016 period, and almost half of treated acreage. Other brassica crops, such as cauliflower, and allium crops, such as dry onion, accounted for slightly more than half of total pounds applied and over 40% of treated acreage. Table 1 reports dacthal applications for brassica and allium family crops as well as all other uses, which were primarily nursery uses and acreage reported as uncultivated or without a crop specified.

A key concern regarding the availability of dacthal is the fate of small acreage brassica crops dependent on dacthal: bok choy, Brussels sprout, radish, kale, rapini, mustards, gai lon, and kohlrabi. Oxyfluorfen is not

Table 1. Dacthal Use by Pounds Active Ingredient Applied and Acres Treated: 2014–2026

	---------Pounds AI Applied-------			------------Acres Treated----------		
	2014	2015	2016	2014	2015	2016
Brassica	137,040	124,375	128,036	37,114	31,967	35,388
Allium	44,350	52,230	54,141	8,540	9,265	9,288
Other	7,872	7,465	6,762	1,803	1,378	1,232
Total	189,262	184,070	188,939	47,457	42,610	45,908

Figure 1. Long-term Dacthal Use Trends and Detections of Dacthal Degradates in Groundwater in the Santa Maria Area*



*Squares represent 1 mile x 1 mile sections that contain previous dacthal use and/or GWPAs. Blue circles represent approximate locations of dacthal degradate groundwater detections.

registered for these crops. Alternative active ingredients such as bensulide and trifluralin provide less effective weed control and/or have long residuals that could interfere with rotational crops common to these cropping systems. Dacthal, in contrast, can be used on many crops and has a short life in the soil, so carryover injury to rotational crops is not an issue.

Dacthal and Groundwater

Dacthal use and detections of its degradates are associated with the Central Coast production areas for Brassica and allium crops. High detections of dacthal degradates in well water in parts of San Luis Obispo, Santa Barbara, and Monterey counties were observed prior to the review. Monterey County alone accounts for about a third of all pounds of dacthal applied, and slightly under half of all acreage treated. Together, San Luis Obispo and Santa Barbara account for around another 10% of pounds applied and 8% of acres treated.

Figure 1 maps long-term dacthal use, whether a focal crop was grown, and detections of dacthal degradates in groundwater in the Santa Maria area in San Luis Obispo and Santa Barbara counties. The highest dacthal use in the area (over the period 1990-2016) occurred south of the Santa Maria River near the community of Guadalupe in Santa Barbara. Figure 2 presents the same information for the Salinas Valley. The highest detections are located near Greenfield.

Approach

The economic impact of a deregistration or other pesticide regulation is determined by its effects on costs, yield, price, and acreage for affected crops. Cost and yield effects depend directly on the chemical and non-chemical alternatives that are available and their prices and efficacy compared to the pesticide being considered for deregistration.

If yield declines, gross revenue will decline. However, if the change in quantity at the industry level is sufficiently large, price may increase, which would partially offset the effect of reduced yield on revenue. Price would only respond to a change in quantity if the industry-level demand was less than "perfectly elastic." If demand is perfectly elastic, then the price does not change when the quantity supplied changes.

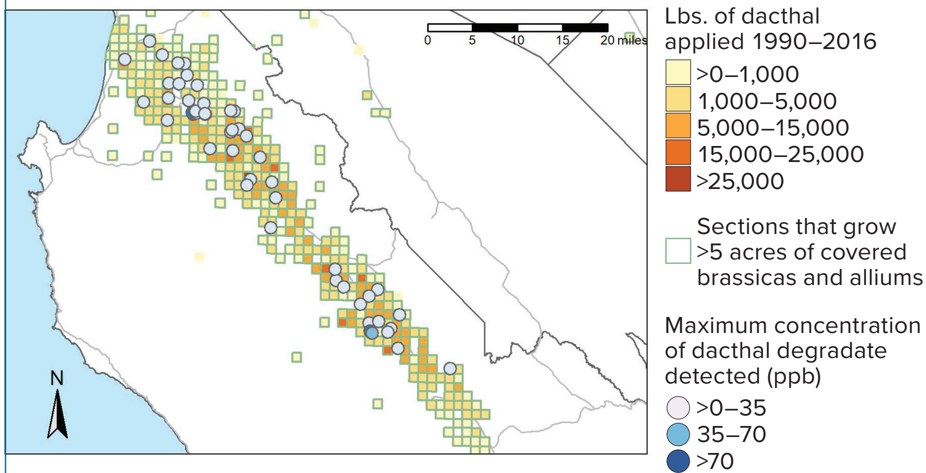
If there are many good substitutes for a crop for consumers and if there are competing producers who can expand output, then the price of a crop will respond less to a given decline in quantity than it would if a crop had few substitutes in consumption and few competing producers. These changes in costs and revenues will affect net returns per acre. Growers may choose to plant fewer acres of the affected crop, which would reduce industry quantity still more and increase price if demand was less than perfectly elastic.

We separate the economic impact of a dacthal deregistration for a crop into four factors: (i) changes in herbicide material costs, (ii) changes in application costs, (iii) changes in hand-weeding and cultivation costs, and (iv) changes in yield, which affect gross revenues.

An overarching challenge is that dacthal does not have a direct substitute and thus one or multiple possible replacement herbicides may provide only partial spectrum of control relative to dacthal. Further, the available set of possible replacement herbicides that are registered depends on the crop in question.

To calculate (i), we begin by identifying one or multiple possible replacement herbicides. The change in material cost is then determined by the amount of material required to achieve a spectrum and level of control as close to dacthal as possible, as well as the price difference between dacthal and the chosen potential replacements. To calculate (ii), we determine if the identified replacement(s) would require changes in the number of applications conducted and thus incur additional application costs. Regarding (iii), additional hand-weeding and/or mechanical cultivation may be needed. Finally, to account for the fact that replacement herbicides may not provide complete

Figure 2. Long-term Dacthal Use Trends and Detections of Dacthal Degradates in Groundwater in the Salinas Valley Area*



*Squares represent 1 mile x 1 mile sections with that contain either previous dacthal use and/or GWPAs. Blue circles represent approximate locations of dacthal degradate groundwater detections.

control relative to dacthal, we calculate (iv) based on an expected yield loss, if any, of incomplete control and current output prices. Given crop-level values for (i)–(iv), we calculate the total economic impact of a dacthal prohibition as the product of the change in per-acre cost for each crop from (i)–(iv) and the number of acres planted to each crop treated with dacthal.

Prior to initiating the analysis, we identified crops that would be most likely to sustain economic losses if dacthal was deregistered: brassica and allium crops. Then we focused attention on determining the crops for which sufficient information was available to conduct the analysis. Pesticide use data were obtained from the DPR Pesticide Use Reporting (PUR) database. Specifically, we collected the amount of active ingredient and treated acreage from 2014 to 2016 from the PUR database for dacthal and all possible replacement herbicides.

Based on this information, 14 brassica and allium crops were identified that used dacthal in that time period and would be impacted by its loss. Ordered by decreasing total pounds of active ingredient applied, the crops are: broccoli, dry onion, cabbage, cauliflower, Chinese cabbage, bok choy, Brussels sprout, kale, rapini, mustard, leek, gai lon, kohlrabi, and green onion.

Crop acreage, production, and price data were obtained from the CDFA annual report. This information was not available for bok choy, rapini, mustard, and gai lon, eliminating them from the analysis. University of California cost studies for broccoli, dry onion, and cabbage were used to provide a baseline for hand-weeding and mechanical cultivation costs and calculate changes in these costs.

Cost studies were not available for seven crops, so only the effects of changes in pesticide costs and yield were included in the computation of the anticipated change in net returns for cauliflower, Chinese cabbage, Brussels sprout, kale, leek, kohlrabi, and green onion. Data limitations mean that the estimate of economic losses is a lower bound for two reasons: not all crops are included, and not all costs are included for most of the remaining crops.

We assume that acreage in each crop remains unchanged. We also assume that demand for these California crops is perfectly elastic. Many of the crops are very minor ones that have multiple close substitutes for consumers. Furthermore, not all acreage utilizes dacthal, dampening industry-level average yield losses and any associated price response. Ex ante, these factors imply that any price increase will be small in response to a given percentage decrease in production.

An offsetting consideration is that California is a major producer, in some cases the only U.S. state with non-negligible production, so that a change in California's output is likely to affect price unless foreign competitors increase production. Any such price increase would reduce losses compared to those reported here.

Results

We focus on changes in net returns for the three crops for which we have information on baseline hand weeding and mechanical cultivation costs: broccoli, dry onion (henceforth onion), and cabbage. Based on the assessment of efficacy presented in the previous section, plus the availability of alternatives given current product registrations, a single alternative active ingredient was selected for each crop. In practice, specific weed problems will influence growers' choice of an alternative pesticide or pesticides, and a variety of herbicides are applied to these crops. PUR data were used to identify a "representative" product for each alternative in order to compute the change in pesticide material costs. Based on product labels and other information, we determined that the alternatives would most likely be applied the same way as dacthal is, so there would be no change in application costs. For broccoli and cabbage, oxyfluorfen (represented by GoalTender) is a partial alternative. For onion, pendimethalin (represented by Prowl H2O) is a partial alternative. While there is substantial use of oxyfluorfen, it does not address early season needs during onion emergence and establishment.

The second step in the analysis is to identify changes in costs and yields. The pesticide material cost per acre of these alternatives is less than the cost of dacthal. Its significant use suggests that differences in yield and other costs are important factors in growers' herbicide use. In the absence of dacthal, hand weeding costs will increase because replacement products do not control weeds as well as dacthal. Based on estimates from UC Cooperative Extension personnel, we assume a 40% increase. Regarding mechanical cultivation, UC cost studies for both organic and conventional broccoli report identical mechanical cultivation costs. In the absence of an organic cost study for cabbage, we assume that mechanical cultivation costs are unchanged, as for broccoli. For onion, we estimate early season cultivation costs will increase by 70%. Based on UC Cooperative Extension estimates, UC cost studies, and the scientific literature, we estimate that there will be a 10% yield loss. If additional hand and mechanical weeding were used exclusively, yield losses would likely be at least 10% owing to the increased need for cultivation and hand weeding, which will damage the delicate crop feeder roots.

Under these specifications, net revenues per acre for broccoli would decrease by $834. Net returns per acre for cabbage would decline by $1,017. Net returns per acre for onion would decline by $590. Information in the cost studies enables us to compare these changes in net revenue to overall net revenue per acre. For broccoli, net returns per acre decreased by 62%. Net returns per acre for onion decreased by fifteen%. Net returns per acre for cabbage decreased by 85%.

If prices are unchanged, the corresponding reductions in statewide net revenues would be $17.9 million for broccoli, $2.4 million for cabbage, and $5.1 million for onion, totaling $25.4 million.

Additional Crops

If DPR had found it necessary to regulate dacthal, there are other regulatory options available. A regional ban or specific use regulations could reduce the impact by focusing on areas with high levels of degradates. Alternatively, dacthal could be added to DPR's groundwater protection list and new groundwater protection areas could be created in order to reduce leaching potential and enhance monitoring and oversight.

Non-regulatory options include enhancing the efficacy of existing alternatives, such as the use of "intelligent" cultivators to reduce hand weeding costs, and pesticides not currently registered for affected crops. One specific possibility would be to screen all brassica crops for tolerance to S-metolachlor (e.g., Dual Magnum). This herbicide active ingredient is gaining many registrations for vegetables and may be helpful for transplanted brassica crops like bok choy. Another would be to expand the set of crops for which oxyfluorfen is registered. Another relatively new herbicide for brassica vegetables is sulfentrazone (Zeus).

Authors' Bios

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For additional information, the authors recommend:

California Department of Pesticide Regulation. "Pesticide Contamination Prevention Act Review Process Triggered by Detections of Chlorthal Dimethyl in Ground Water." www.cdpr.ca.gov/docs/emon/grndwtr/chlorthal_dimethyl/chlorthal_dimethyl.htm.

Bt Eggplant in Bangladesh Increases Yields and Farmers' Incomes, and Reduces Pesticide Use

Ahsanuzzaman and David Zilberman

Genetically engineered (GE) Bt eggplant was introduced to Bangladesh in 2013 and by 2017, 18% of eggplant growers have adopted it. Our study, based on a survey of 481 farmers, indicates that adoption of Bt eggplant increases yield and profits. Farmers receive higher prices for GE eggplant compared to other varieties. The technology also reduced pesticide applications and thus has the potential to improve health and reduce environmental damage of farming. The level of adoption is likely to increase, and the success of Bt eggplant may lead to the adoption of GE varieties in other vegetable crops.

Genetically engineered (GE) crop varieties were introduced in the early 1990s and have been widely adopted in the production of feed (corn, soybeans) and fiber (cotton) crops. GE has seldom been adopted with crops used directly for human consumption, including grains like wheat and rice and especially vegetables and fruits. There is a wide variety of evidence that GE crops do not present more risk than traditional crops. Furthermore, the major beneficiaries of such crops are likely to be producers and consumers in developing countries.

The barriers to the adoption of GE crops are regulatory, as well as a perception of strong consumer resistance, expressed in low willingness-to-pay for the crops. This paper presents the results of an important case study of the adoption and impacts of a GE food variety: Bt eggplant (brinjal), which was developed by South Asian scientists and introduced in Bangladesh in 2013. This paper provides background on Bt eggplant and Bangladesh, an assessment of the impacts of Bt eggplant, and a discussion of the challenges of adoption.

Background

Eggplant is a diet staple in Bangladesh, it ranks third after potato and rice among vegetables in the country in quantity consumed, and thus it is important for food security. About 150,000 farmers grow eggplant on approximately 50,000 hectares in two seasons: winter and summer. The productivity of eggplant farming in Bangladesh has been relatively low because of insect damage that reduced yield by two-thirds, despite efforts to introduce insecticide and cultural practices. Eggplant productivity could be raised substantially if the crop's major pests could be managed effectively.

Due to heavy infestations of multiple pest species, crop production has relied intensively on insecticides. This has led to economic losses and human health damage. Research efforts by the Bangladesh Agricultural Research Institute (BARI), with the support of Maharashtra Hybrid Seeds Company Private Limited (Mahyco), developed Bt eggplant as a long-term solution to the pest problem. Bt eggplant is a genetically modified eggplant that carries an additional gene providing built-in protection against pests. With the introduction of Bt eggplant in 2014, Bangladesh became the 29th country to grow a genetically-engineered crop. By 2017, over 27,000 farmers were growing Bt eggplant in Bangladesh.

Currently, farmers apply insecticides on a daily or twice-daily basis up to 140 times per season. Continuous use of pesticides becomes ineffective due to pest resistance to the insecticide. Furthermore, heavy use of chemical insecticides results in pollution and health hazards to both producers and consumers. In October 2013, the government of Bangladesh released four genetically modified varieties of Bt eggplant for seed production and initial commercialization.

The South Asia Eggplant Improvement Partnership initiated the development of Bt eggplant with support from the U.S. Agency for International Development (USAID). BARI then introduced the Bt trait into commercially popular, open-pollinated eggplant varieties in Bangladesh. This allowed the establishment of a diversity of local varieties with GE traits. Out of the nine popular varieties that were modified with Bt event EE-1, four were approved for commercial cultivation in October 2013.

The cultivation of Bt eggplant started in spring 2014 by 20 small eggplant farmers in 2 hectares of land in four representative districts—Gazipur, Jamalpur, Pabna, and Rangpur. The appropriate varieties were selected for each district. BARI played the key role as the only organization in the first three years (2013-2015) to disseminate the new technology to farmers on a small scale. BARI's program led to 108 farmers in 2014-15 season, and 250 farmers in 2015-16 season to adopt the new technology. Extension agents in the Department of Agricultural Extension (DAE) started to disseminate the new variety in 2016, followed by the Bangladesh Agricultural Development Corporation (BADC) in 2017.

Initially, the dissemination was directed by the government and extension (DAE) and led 6,000 farmers to adopt the Bt eggplant, the development corporation (BADC) dissemination activities significantly expanded adoption

Table 1. Market Price (Bangladeshi Taka) Information

	Bt	Non-Bt	Bt Premium
Wholesale	15.45	11.7	32%
Retail	28.6	22.35	28%
Mark up	13.5	10.65	27%

and led an additional 19,430 farmers to adopt Bt eggplant. In total, 27,012 farmers have adopted the new variety by the spring 2018 season, and there is still potential for much higher adoption rates, as approximately 150,000 farmers grow eggplant in the country.

The success of Bt eggplant has led the government of Bangladesh to sanction the field testing of three other genetically engineered crops—a GE disease-resistant potato, Bt cotton, and golden rice. Other crops are undergoing research as well, such as BARI's work on a GE tomato resistant to the leaf curl virus, Dhaka University's trial to develop salt-tolerant rice, and Dhaka University's research on GM fungal-resistant peanuts, lentils, chickpeas, and mung beans.

Despite this interest in GE crop varieties, there are very few studies that assess the effectiveness of Bt eggplant in Bangladesh, and those that exist are mostly based on experimental plots. None so far evaluates the effectiveness of Bt eggplant using farmers' field data collected by farmers cultivated in a non-experimental set-up. We bridge this gap by evaluating the cost-effectiveness of Bt eggplant using farm-household survey data from Bangladesh.

Assessment of Bt Eggplant in Bangladesh

We conducted a survey of 500 farmers in 8 districts of Bangladesh—Comilla, Mymensingh, Jamalpur, Sherpur, Kushtia, Meherpur, Gazipur and Narsingdi. The districts were chosen intentionally to represent areas where Bt farmers are available. Farmers in our survey adopted the Bt eggplant by purchasing seed from stores, rather than receiving seed for free from a government program. Among 500 farmers surveyed, 301 grew Bt eggplant. Among Bt farmers, 18 grew both Bt and non-Bt varieties. In order to estimate the differential outcomes, we used the farmers who grew either only Bt or non-Bt varieties. This led our final sample size to be 482.

The average age of farmers in our survey is 42.89 years, with 4.22 years of schooling, 5.25 total members in the family, 0.57 acre vegetable farm size, 93% of whom are married, 79% of whom are members in a community organization, and with an average home distance of 2.64 kilometers (km) away from local bazaar. There is no statistical difference on observable characteristics between adopters and non-adopters.

We first identified the factors that affect adoption. We found an increased adoption of Bt eggplant among farmers over time, both in terms of number of adopters and in acreage. We estimated the factors that increase the likelihood of increased adoption of Bt eggplant, and find that large farmers with mostly grains and rice have a lower likelihood of adoption than larger vegetable farms. Credit is very important and farmers with access to a bank, and in particular with a bank account at the local commercial bank, are more likely to adopt. Location also matters and farmers mostly living near local markets and having nearby Bt eggplant plots are more likely to adopt. Finally, the likelihood of adoption increases with age and with membership in a community.

Table 2. Comparative Production Outcome

Type	Yield (ton)	Total Area (acre)	Yield (Tons/acre)
Bt	844.13	67.85	12.44
Non-Bt	861.54	61.13	7.55
Total	1305.67		65% increase

In addition to a farmer survey, we also collected data on the market prices of Bt and non-Bt eggplant at both retail and wholesale levels. The results in Table 1 show that Bt prices are higher than non-Bt prices at both the retail and wholesale levels. A higher wholesale price for Bt eggplant suggests that farmers are receiving higher prices for the Bt variety while higher retail prices for Bt eggplant might indicate that consumers are willing to pay more for Bt varieties. Furthermore, the retailer receives a higher premium (difference between wholesale and retail price) for Bt varieties. The results suggest around a 30% price premium at all levels for the Bt varieties.

The major reasons for higher prices for Bt varieties mentioned by the respondents are that they look fresher, they have fewer blemishes, and most importantly, they do not have holes that are present in non-Bt eggplants from pest invasions. This finding contrasts with most of the previous literature, which presumes that consumers are willing to pay less for GE varieties than non-GE varieties. Here, we find that once GE products have preferred observable characteristics, they obtain a positive premium. Better product quality trumps some of the presumed objections to GE among the buyers.

Our sample covers eggplant farming on 129 acres of land for both Bt and non-Bt varieties (see Table 2). The production data show that yield per acre of land is higher by 65% for Bt varieties than non-Bt ones. The adoption of Bt eggplant seems to increase yield, but also increases total cost of production (Table 3). The increase in total cost is due to the higher price of seed and higher labor costs associated with high yields. However, adoption of Bt eggplant reduces average chemical pesticides cost per acre. More importantly, not only are the chemical pesticide costs lower for Bt varieties than non-Bt ones, but the pesticide costs as the percentage of total cost are much lower (15%) for Bt eggplant than that of non-Bt ones (24%). Controlling for the major pests responsible for substantial yield requires pesticide use. Focusing on farming practices, average spraying per week for Bt varieties was found to be 32% lower than that for non-Bt eggplant cultivation (t=17.47).

Table 3. Total Cost Information (in Bangladeshi Taka. [1USD=approx. 82 Taka])

	Bt	Non-Bt
Total cost (TC)	235,100	211,716
Chemical Pesticide Costs	34,478	51,370
	15% of TC	24% of TC
	33% reduction in TC	
Spray/week	3.11	4.58
	32% lower	

The outcomes reported above are based on average outcomes in the sample. To further assess these outcomes, we apply econometric models to estimate the impact of Bt eggplant variety adoption on its profitability and to identify variables that are statistically significant. While investigating the source of increased profit, our results show that adoption of Bt eggplant raises yield by 17%–26% compared to non-Bt varieties. We find that Bt farmers spray 1–2 times less per week compared to non-Bt farmers, and thus Bt eggplant farmers incur between 52%–98% lower pesticides cost per acre compared to that associated with non-Bt eggplant farming.

While having lower pesticide costs, Bt eggplant farmers have higher seed and labor costs (relating to the higher yield). Therefore, there is no statistically significant difference in cost of farming per unit of land between Bt and non-Bt varieties of eggplant. But with higher yields of Bt eggplant, cost per unit of output is lower. Altogether we find that Bt eggplant adoption increases profits by 25%–63%. Furthermore, adoption of Bt eggplant and the reduction of pesticide applications associated with it are likely to lead to improved health status and better environmental quality.

Our survey also collected information about the potential challenges associated with Bt eggplant. We find that farmers are not aware of the details of the new variety and the benefits and costs associated with it. Respondents are not well-trained on how to farm the new variety or the potential benefit associated with the Bt variety. In some cases, they spend more money on inputs that are not necessarily required, such as plot preparation, fertilizer use, irrigation, etc. Learning by doing associated with continuous use of the technology, as well as extension efforts can change farmer perceptions and improve their practice and enhance the benefits from adoption of Bt eggplants.

Conclusion

Introduction of Bt eggplant to Bangladesh is significant because it is one of the first GE vegetables introduced to the Indian subcontinent and one of the first GE-modified crops intended for direct human consumption. We surveyed 481 farmers in eight districts in Bangladesh, and found that adoption of Bt eggplant increased yield and raised profits. While there is no difference in cost per acre of farming eggplant between Bt and non-Bt varieties, costs per unit of eggplant is lower with Bt because of its higher yields.

Adoption of Bt eggplant also reduces pesticides sprays substantially compared to non-Bt varieties and thus improves farms safety. These results are consistent with the outcomes of studies of adoption of Bt cotton and Bt corn. Furthermore, farmers received a higher price for Bt eggplant, which shows that if GE products have desirable attributes to consumers, they will be able to fetch higher prices. We also find that the farmers didn't receive much guidance and information that could improve performance with the technology. Thus, if information about Bt eggplant is disseminated and farmers are well-trained, it might increase profitability even further and improve food security, farmer health, and environmental quality in Bangladesh.

This paper illustrates the large economic and health gains from adoption of GE technology in vegetable crops. Adoption of GE crops in vegetables may increase supply through higher yield and reduce cost per unit of output, and thus reduce price—improving food security. It will also likely improve worker safety in agriculture, by reducing exposure to pesticides. These impacts are especially significant in developing countries, so efforts should be made to reduce excessive barriers to adoption of GE varieties in crops consumed directly by humans. Finally, as the case of Bangladesh indicates, consumers will be willing to pay even more for Bt varieties if they have apparent advantages.

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