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Dacthal Economic Benefits Analysis

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Overview

- The economic analysis quantifies the direct and indirect economic benefits of Dacthal

- Standard economic benefit-cost analysis:
  - Compare net farm income pre/post Dacthal restrictions considering the next best (least cost) alternative to Dacthal
  - Quantify other indirect benefits, including retail supply chain value

- Benefits
  - Avoided cost (labor cost, alternative materials)
  - Gross revenue (minimal yield and/or crop quality losses)
  - Indirect economic effects

Acreage and Value Overview

- Acreage typically treated with Dacthal includes:
  - Onions, broccoli, cauliflower, cabbage, Brussels sprouts, and Asian vegetables

- Acreage that could be treated with Dacthal generates total annual gross value of $1.7 – $3.8 billion per year
  - The share of acreage treated with Dacthal ranges from 12 to 30 percent
  - Acreage treated with Dacthal generates gross farm value of $350 - $800 million per year

- Dacthal sales supply chain generates gross value of $5 - $6 million/year

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Economic Methodology

- Identify acreage, crops, regions, typically treated with Dacthal
  - DPR Pesticide Use Reports (2005-2016)
- Quantify cultural practices, Dacthal use, alternative herbicides, and costs
  - Literature review, UCCE cost studies
  - Survey/interviews of UCCE Farm Advisors, PCAs, industry experts, growers
  - Identify the least-cost alternatives to Dacthal
- **Direct benefits**: Stochastic farm budget models measure the effect of Dacthal on net farm income and profit risk
  - Dacthal and least cost alternative
- **Indirect benefits**: Changes in economic activity in industries that are linked to agriculture
  - Also called "multiplier" effects
  - Additionally include the retail supply chain economic value

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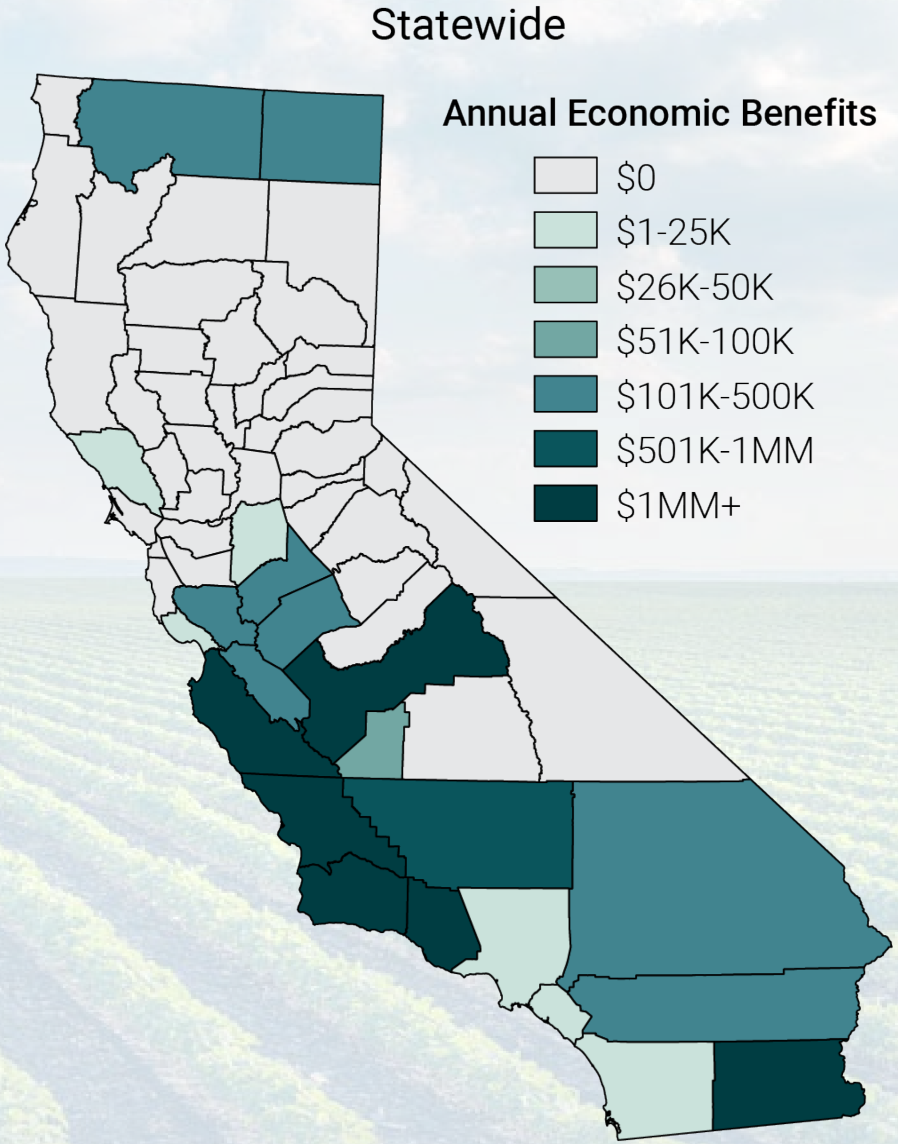
Statewide Benefits Summary

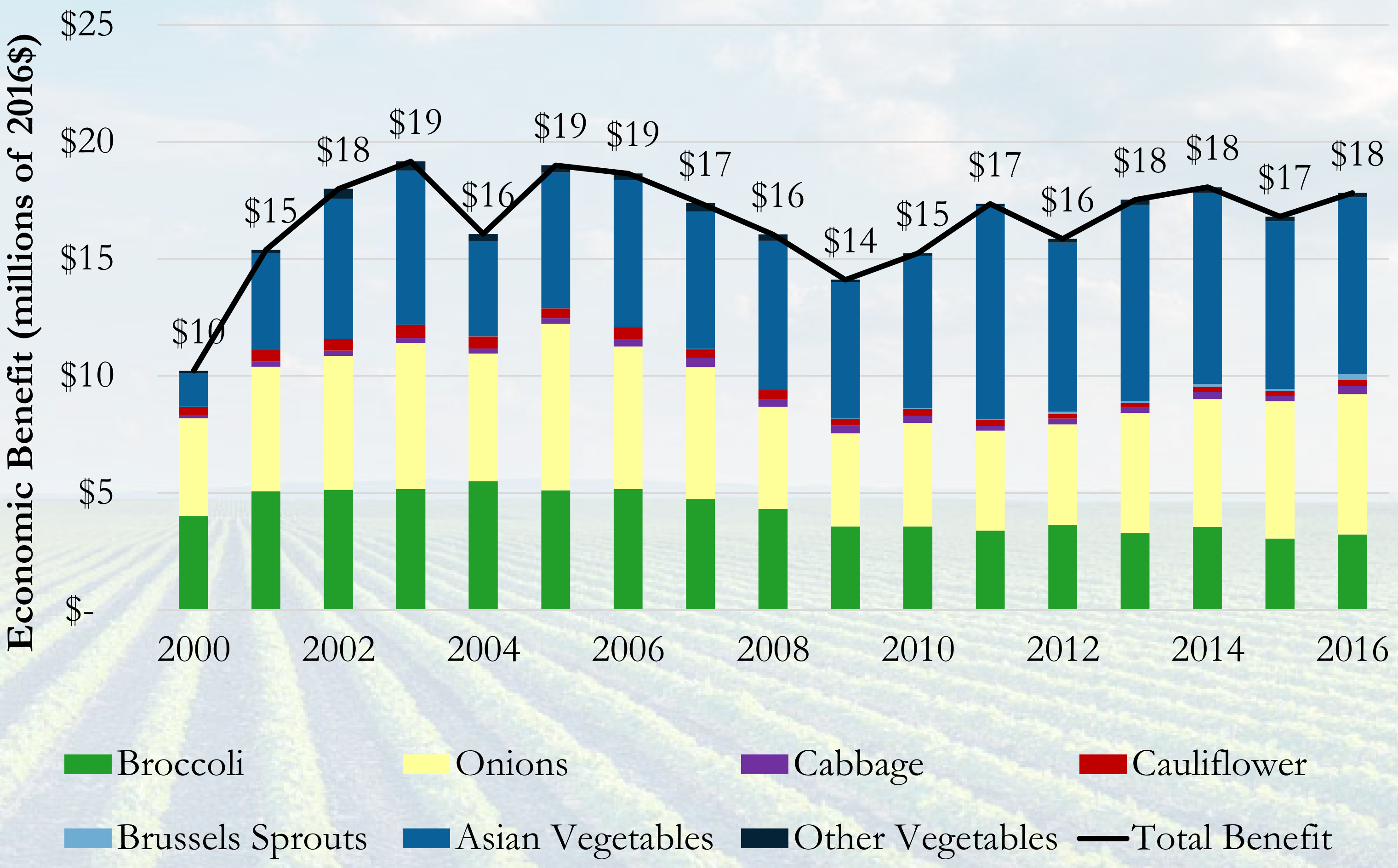
- Crop benefits: $10 - $17.0 million/yr (total including multiplier effects)
  - Labor scarcity
  - Yield and quality losses
- $5 - $6 million per year in sales generates $10 - $11 million per year in total economic benefits
- Total benefit range of $20 - $37 million per year
- Important result
  - There are alternatives to Dacthal, but these require additional labor
  - Labor is scarce and increasingly costly



Dactal Statewide Benefits

- Benefits concentrated in high value vegetables:
  - Onions: 31%
  - Broccoli: 23%
  - Asian vegetables: 41%
- Brussels sprouts small, but growing
- Annual benefit range
  - $10 - $17 million

Total Economic Benefit	
2000-16 per acre average	$340



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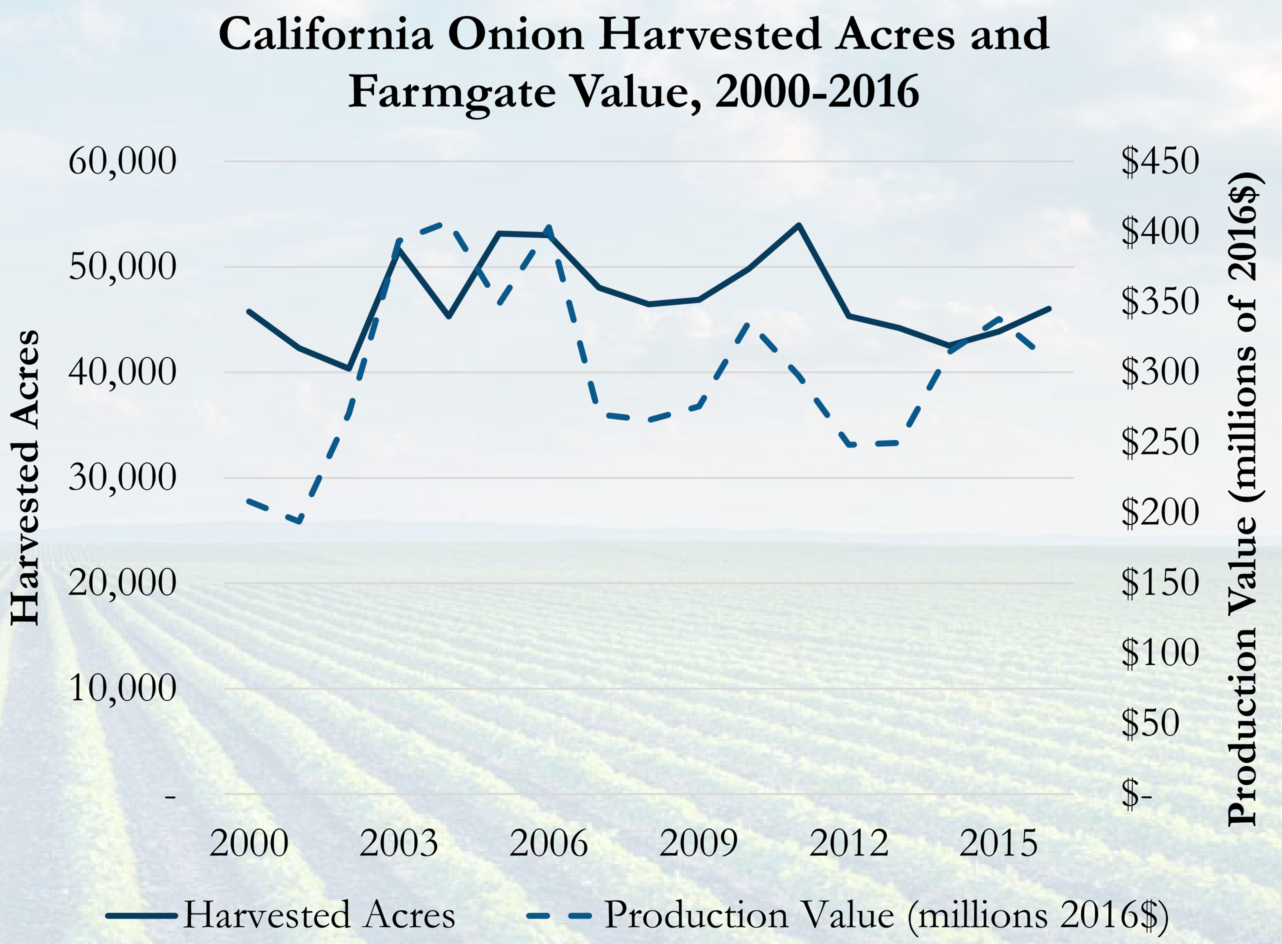
Onion Overview

- 47,000 acres; $301 million value
- 89% of acreage in 4 counties
  - Fresno: 17,000 acres
  - Imperial: 13,700 acres
  - Kern: 7,600 acres
  - Monterey: 2,200 acres
- 45% of crop to fresh market
  - US consumption per capita up 16% since 2000, total consumption up 34%
- Approximately 1/3 of California onions are exported ($83 m)
- Acreage and total value steady



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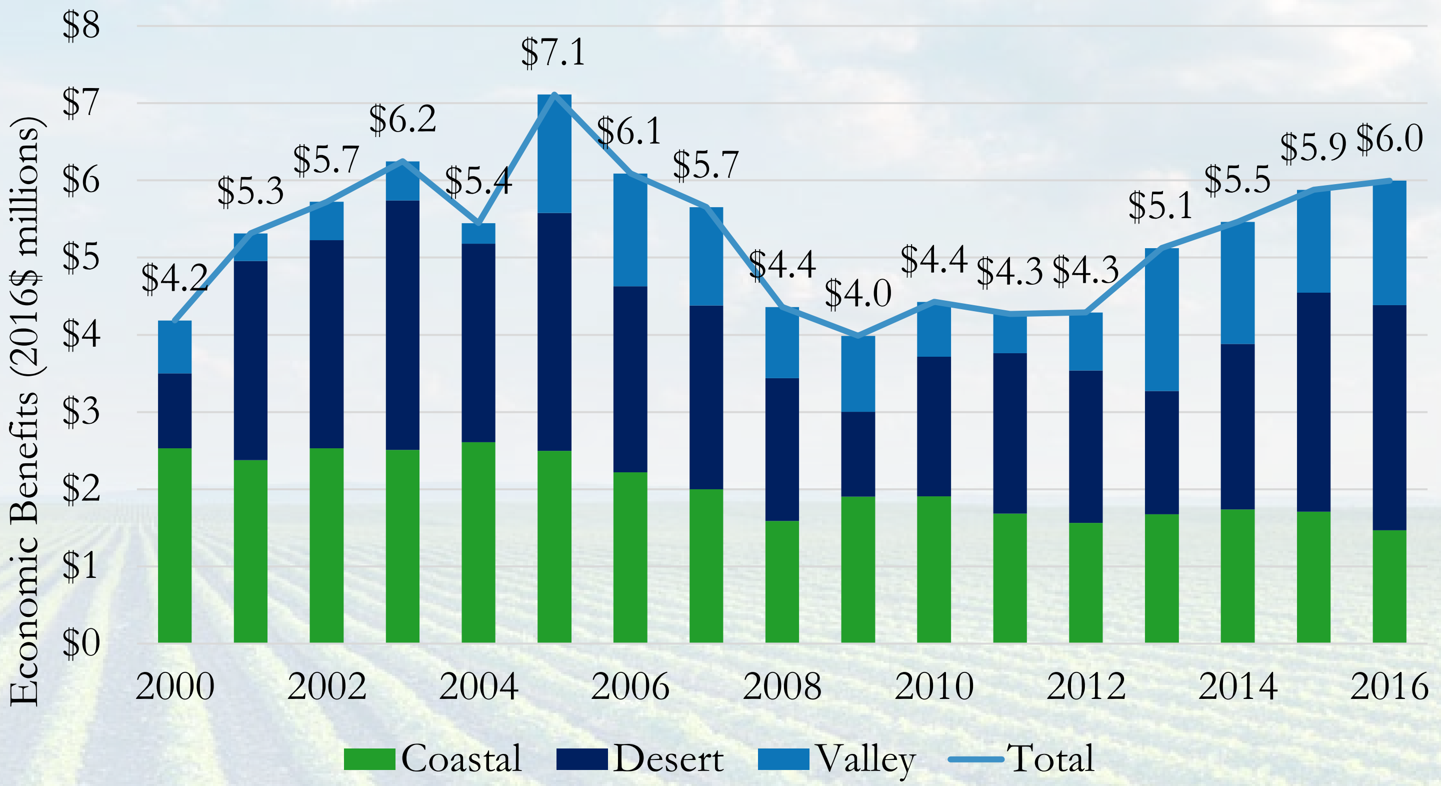
Dacthal Onion Benefits

- Dacthal alternatives increase production cost by $51/acre
  - Reduced material cost, increased hand-weeding cost

- Alterative reduces yield by 5%, resulting in loss of $606/acre

- Annual benefit range
  - $4 - $7 million



Total Economic Benefit	Onion
2000-16 per acre average	$657

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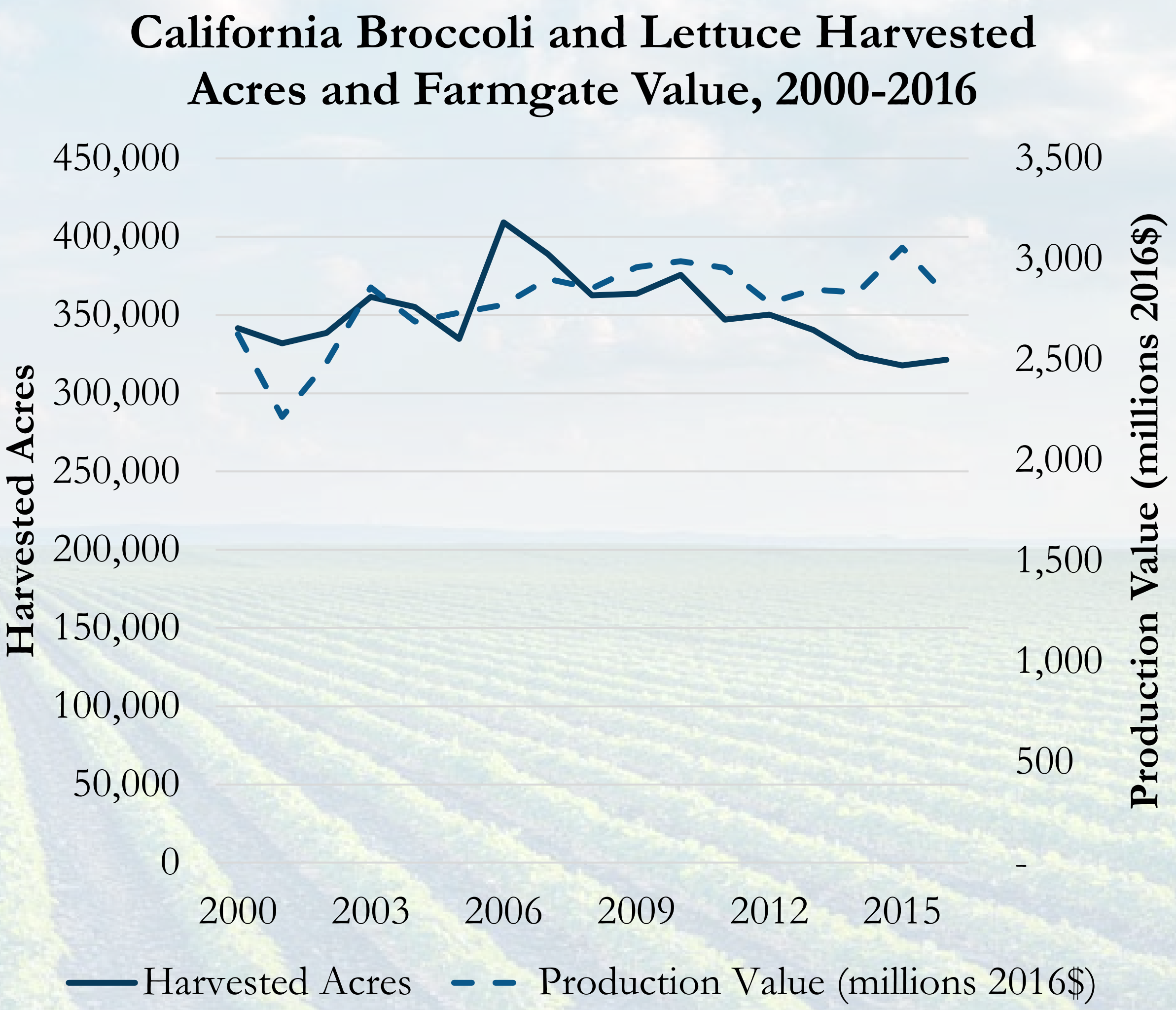
Broccoli Overview

- 120,000 acre; $785 million value
- 83% production in 3 counties
  - Monterey: 58,000 acres
  - Santa Barbara: 25,000 acres
  - Imperial: 15,000 acres
- Typically grown in lettuce, melon, or other vegetable rotations
- Acreage steady; value growth
  - Per capita consumption up 20% since 2000 (10.1 lbs)



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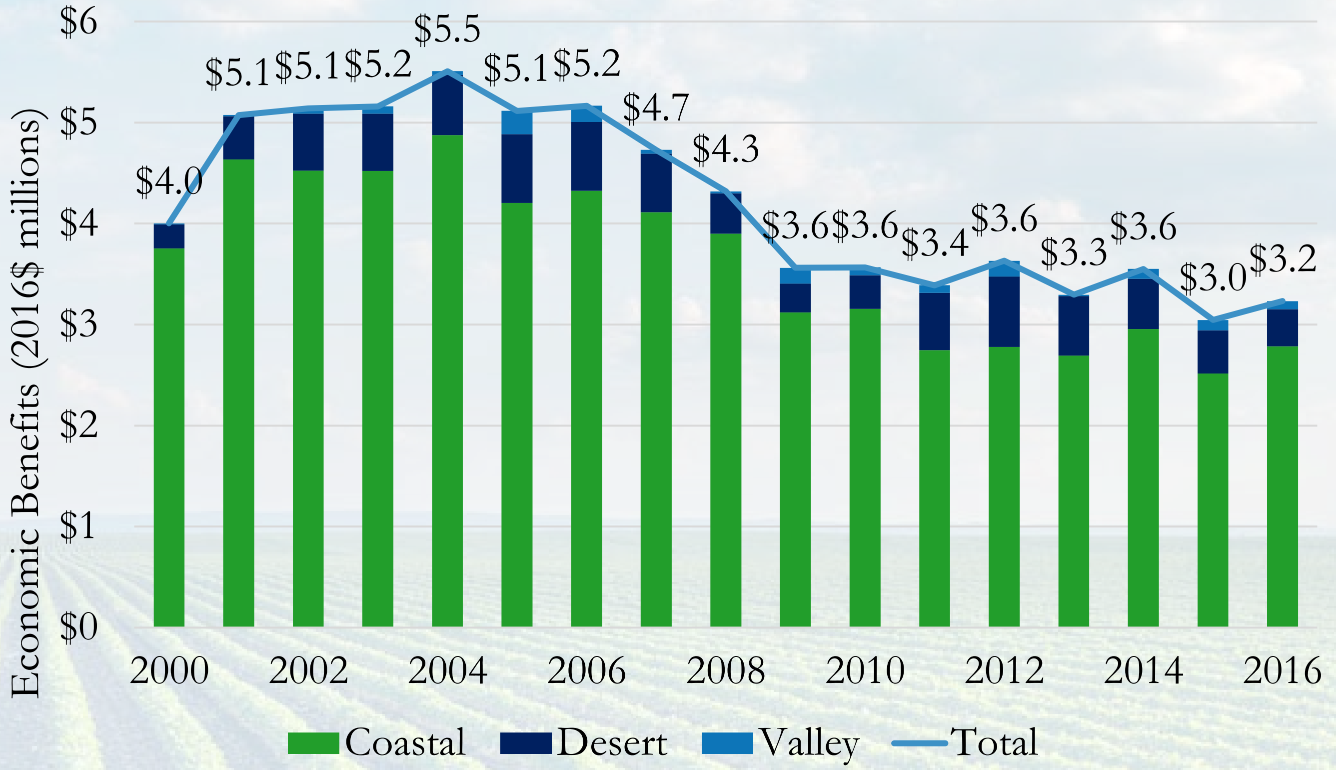
Dacthal Broccoli Benefits

- Dacthal alternatives increase production costs by $143/acre
  - Reduced material cost, increased hand-weeding cost
  - Alternatives herbicides have lower material cost, but higher hand weeding requirements

- Annual benefit range
  - $3 - $5.5 million



Total Economic Benefit	Broccoli
2000-16 per acre average	$143

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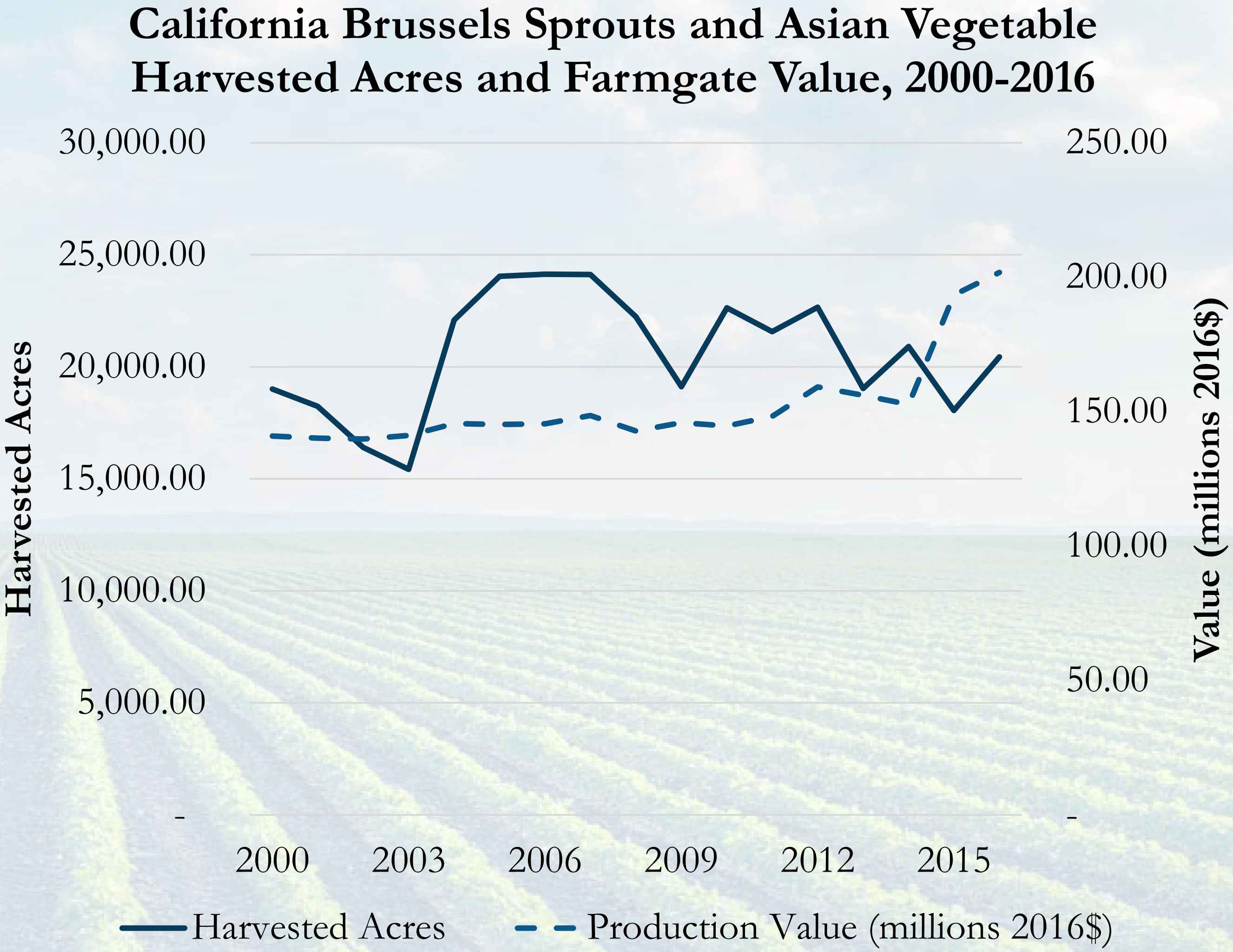
Brussels Sprouts and Asian Vegetables Overview

- Brussels sprouts
  - 5,300 acres; $74 million value
  - Produced in coastal counties
  - Strong growth in fresh market
    - Consumption/capita up 72% since 2014 (0.8 lbs)
- Asian vegetables
  - 15,000 acres; $152 million value
  - Acreage varies
  - Market growth in recent years
    - Nearly exclusive for the domestic fresh market



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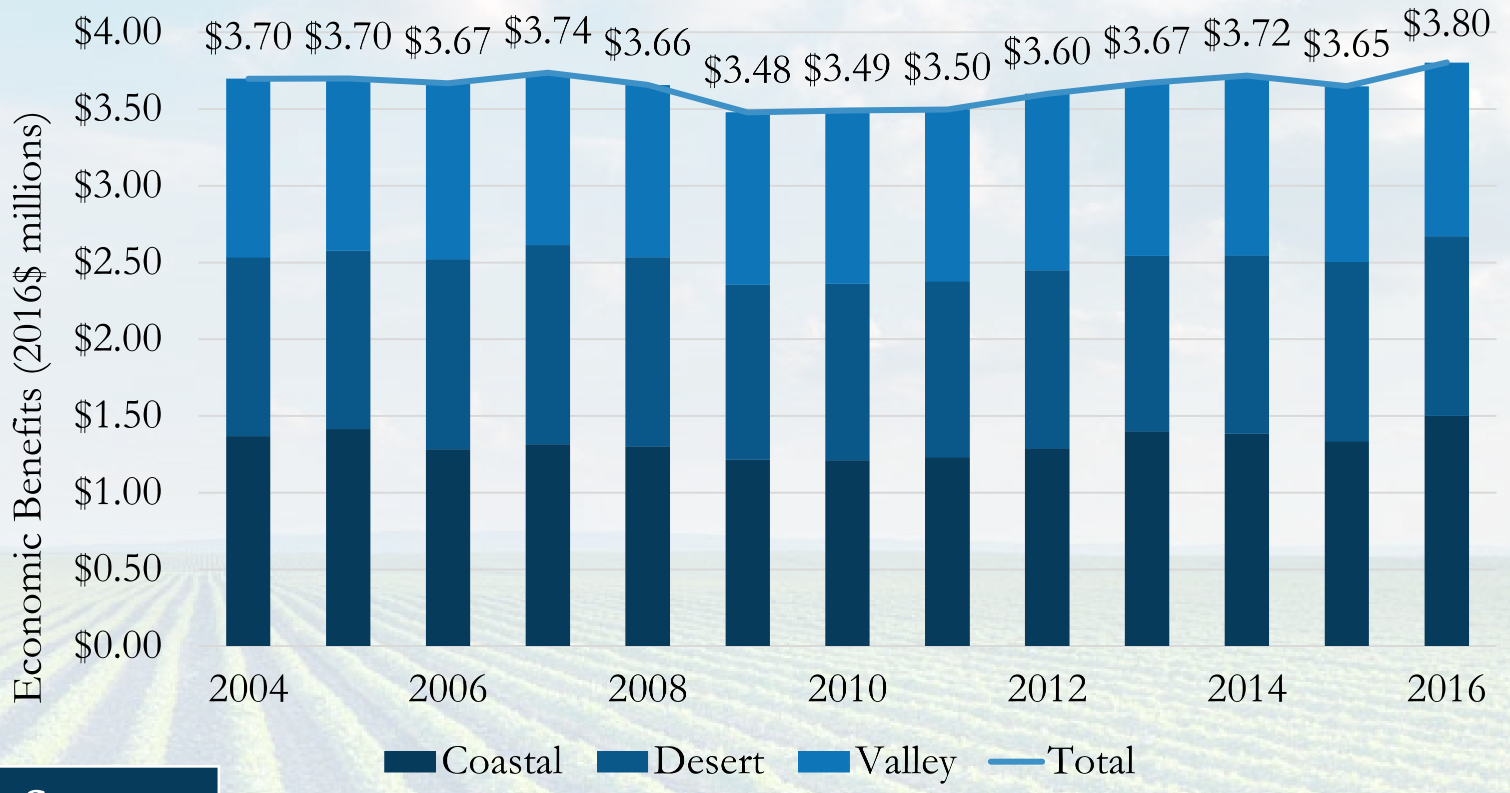
Dactal Brussels Sprout and Asian Vegetable Benefits

- Dacthal alternatives increase production cost by
  - $120/acre (Brussels Sprouts)
  - $128/acre (Asian Vegetables)
  - Reduced material cost, increased hand-weeding cost

- Potential crop damage for Asian Vegetables (modeled at 5%)



Total Economic Benefit	Brussels Sprouts
2000-16 per acre average	$120

Total Economic Benefit	Asian Vegetables
2000-16 per acre average	$1,360

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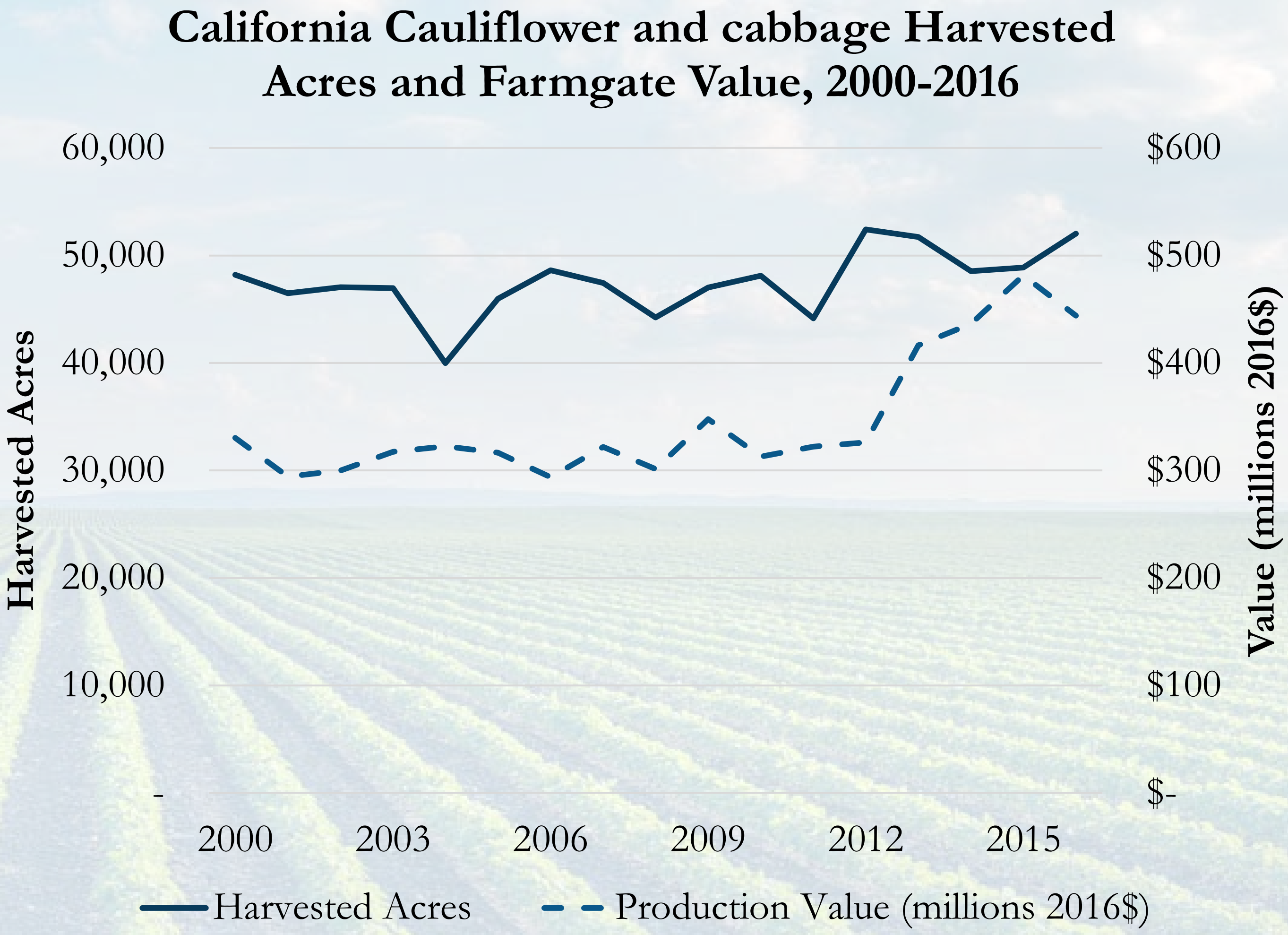
Cauliflower and Cabbage

- 52,000 acres; $445 million value
- Over 85% of cauliflower and cabbage acreage in Monterey, Santa Barbara, Imperial, and Santa
- Fresh market cauliflower demand growth
  - Consumption/capita up 25% since 2000 (2.18 lbs)
  - 88% of US exports are from California
- Cabbage consumption per capita has stabilized, exports are currently around $12 million annually



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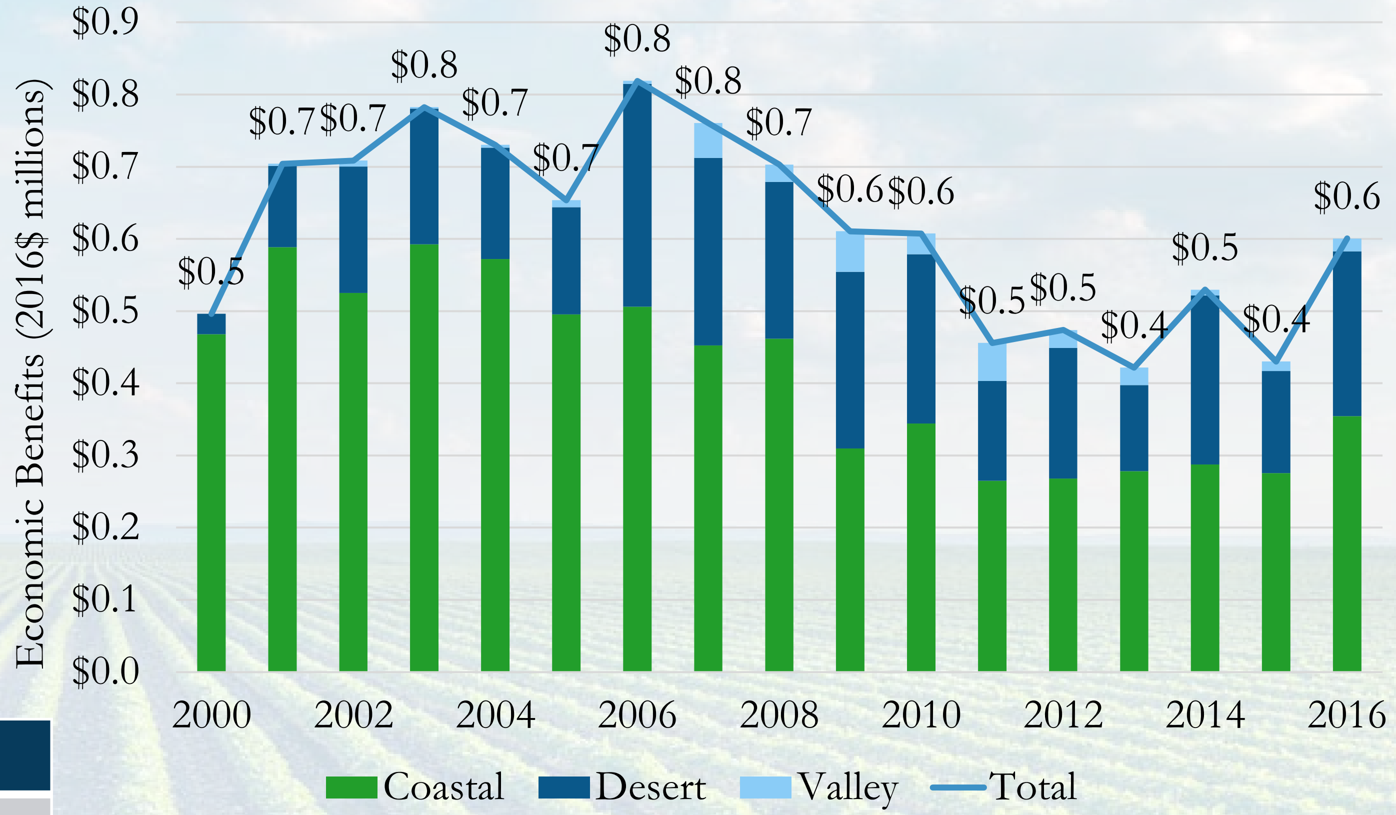
Dactal Cauliflower and Cabbage Benefits

- Dacthal alternatives increase production cost by:
  - $87/acre (cauliflower)
  - $125/acre (cabbage)
  - Comparable material cost, increased hand-weeding cost

- Annual benefit range
  - $400K - $800K

Total Economic Benefit	Cauliflower
2000-16 per acre average	$87

Total Economic Benefit	Cabbage
2000-16 per acre average	$125



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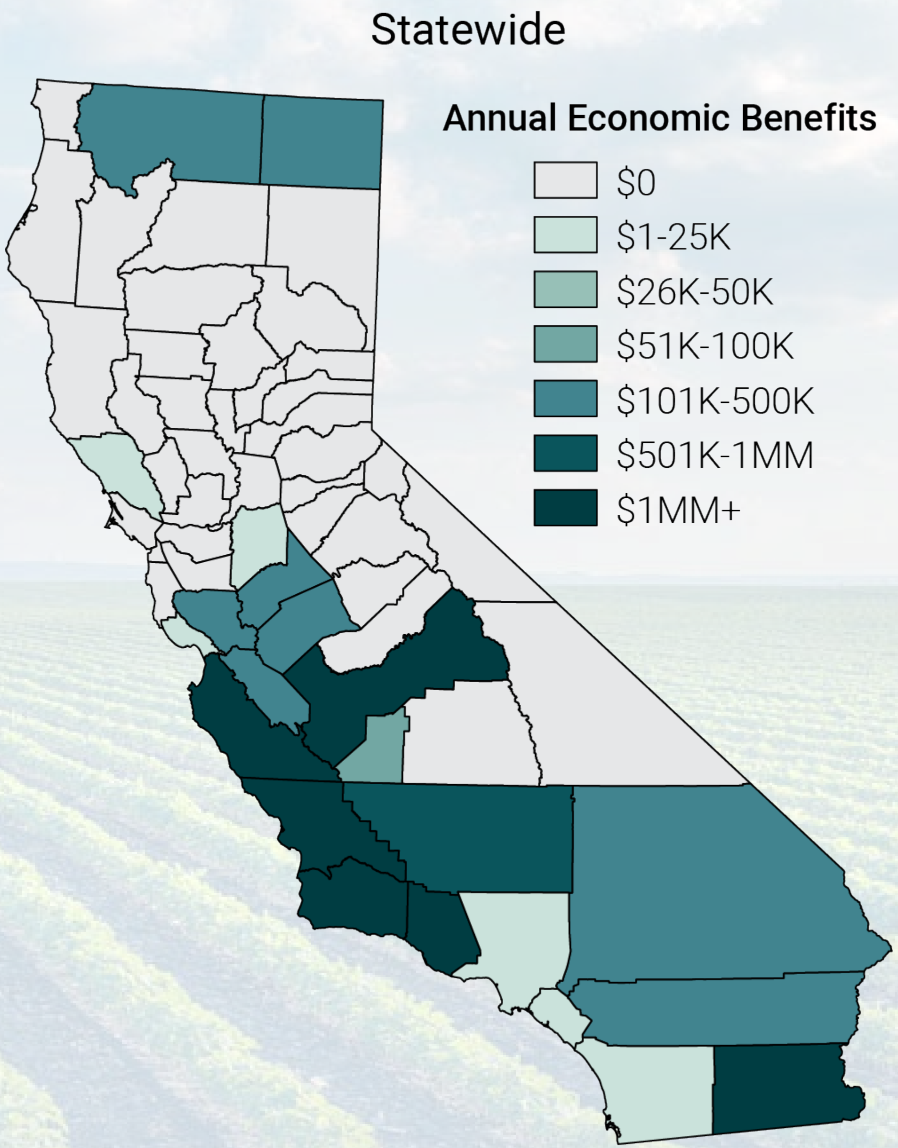
Dactal Benefits Summary

- Dacthal Benefits:
  - $10 - $17 million/year for crop production
  - **$20 – $37 million/year in total**
- Dacthal increases variability in net farm income by 4% on average (1.5% – 9%)
- Uncertainties
  - Labor is increasing scarce and costly in California; economic benefits increase if growers are not able to secure labor supply
    - AB 1066 and immigration reform
  - The joint effect of other regulations
  - Greater yield losses will increase benefits



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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

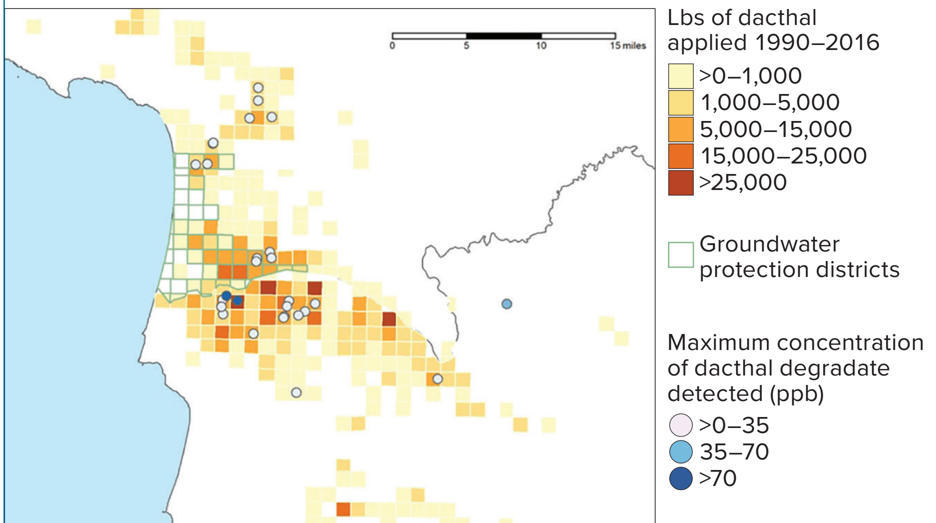
Dacthal is a selective pre-emergence herbicide used for controlling annual grasses and certain broadleaved weeds. The value of dacthal is its long list of crop registrations and excellent selectivity on a large number of crops in the allium (onion family) and brassica (mustard family) crops, which account 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 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.

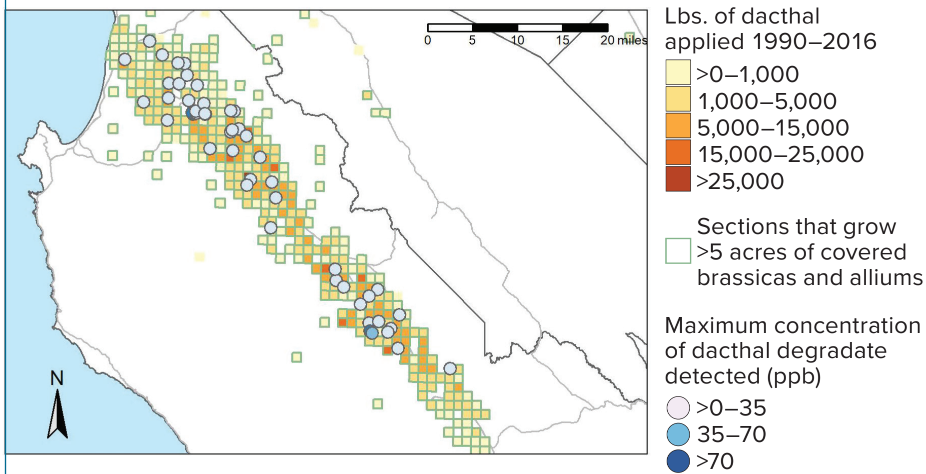
Prior to initiating the analysis, we identified crops that would be most likely to sustain economic losses if dacthal was deregistered: brassica and allium crops. Then we focused attention on determining the crops for which sufficient information was available to conduct the analysis. Pesticide use data 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.

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.

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

Steven Blecker and Kevi Mace are senior environmental scientists in the Office of Pesticide Consultation and Analysis, California Department of Food and Agriculture and research associates in agricultural and resource economics at UC Davis. Steven Fennimore is extension specialist and weed ecophysiologist in the Department of Plant Sciences at UC Davis. Rachael Goodhue is professor and chair, Tor Tolhurst and Hanlin Wei are Ph.D. students, and Daniel Tregeagle is post-doctoral scholar, all in the ARE department at UC Davis. John Steggall is senior environmental scientist in the Office of Pesticide Consultation and Analysis, California Department of Food and Agriculture and research associate in the Department of Land, Air and Water Resources at UC Davis. Goodhue can be contacted by email at goodhue@primal.ucdavis.edu.

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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.

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An Economic and Pest Management Evaluation of the Herbicide Dacthal in California Agriculture

Prepared for
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Office of Pesticide Consultation and Analysis

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Abstract

A formal review of dacthal (aka chlorthal-dimethyl or DCPA) was initiated by the California Department of Pesticide Regulation (DPR) as required by the Pesticide Contamination Prevention Act due to the detection of its degradates in groundwater. The purpose of the formal review process is to determine whether dacthal can continue to be used and, if so, under what conditions. In this report we evaluate the potential economic impacts to crops that are significant users of dacthal if the outcome of DPR's 2018 review process results in deregistration of dacthal. This report is part of the interagency consultation between the DPR and the Office of Pesticide Consultation and Analysis (OPCA) in the California Department of Food and Agriculture (CDFA).

Dacthal is a selective pre-emergence herbicide used for controlling annual grasses and certain broadleaved weeds. In California, agricultural uses are primarily for vegetable crops. Dacthal is a niche herbicide used in crops with few alternative herbicides that have similar selectivity and efficacy as dacthal. Currently (as of 08/07/2018), there is just one actively registered dacthal product.

Brassica and allium crops account for the majority of dacthal use. Broccoli alone accounted for 40 percent of pounds applied in the 2014-2016 period, and almost half of treated acreage. This report evaluates statewide impacts. Owing to the high detections of dacthal degradates in wells in Monterey, San Luis Obispo, and Santa Barbara counties, the report also presents information for these three counties individually.

The primary pest management issue is that dacthal does not have a direct substitute and thus one or multiple possible replacement herbicides may provide only partial spectrum of control. The availability and efficacy of alternative herbicides varies significantly by crop. The main concern for the loss of dacthal would be for small acreage crops dependent on dacthal: bok choy, Brussels sprout, radish, kale, rapini, mustards, gai lon and kohlrabi. Alternative AIs 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. Onion has no alternative to dacthal during the preemergence stage. However, while not a direct dacthal substitute, oxyfluorfen is safe for broccoli, cauliflower, and cabbage and effective on a number of key weeds.

While hand weeding and cultivation are essential to weed control programs including dacthal, under a deregistration scenario the incomplete spectrum of control provided by alternative herbicides would lead to increased hand weeding and cultivation costs. Even with increased weeding, dacthal deregistration could result in non-trivial yield losses. Further, although we do not account for this in our analysis, increased weeding costs could be exacerbated by the high cost and increasing shortages of labor.

The economic analysis in this report uses a partial budgeting approach and separates the economic impact of a dacthal deregistration 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. The amount of information available, and hence the factors considered in

the calculation of effects on net revenue, varies by crop. For some crops, no information regarding yield is available, so the only factor considered is the change in herbicide costs. Herbicide cost changes tend to be small on a per-acre basis. Alternative herbicides are sometimes less expensive than dacthal, perhaps reflecting their lower efficacy and reduced spectrum of control, so analysis based only on this factor will understate the true costs of deregistering dacthal.

For seven crops, yield and price information is available, so the calculation of net revenue includes the change in herbicide costs and the change in gross revenues due to projected yield losses. The crops are cauliflower, Chinese cabbage, Brussels sprout, kale, leek, kohlrabi, and green onion. Total losses for these crops statewide, if dacthal were removed from use, are $6.4 million if yields decreased by 10 percent, and $13.9 million if yields decreased by 20 percent. Losses vary by crop. The largest impacts would fall on cauliflower (-$2.1 to -$4.4 million), Chinese cabbage (-$1.2 to -$2.7 million), and Brussels sprout (-$1.5 to -$3.3 million). Green onions have the largest change in net returns per acre, but the smallest change in total cost, owing to small planted acreage planted. It is likely that hand weeding and mechanical cultivation costs would increase with these crops, but no data are available, so these costs were not included in the analysis. Therefore, these cost estimates underestimate the total cost change.

For broccoli, onion and cabbage, information is also available on hand weeding and mechanical cultivation. This additional information paired with estimated changes in each factor generates a large number of scenarios. The most likely scenarios for broccoli and cabbage are a 10 percent yield loss, a 40 percent increase in hand weeding costs, and no change in cultivation costs; and for onions, a 10 percent yield loss, a 40 percent increase in hand weeding costs, and a 71 percent increase in cultivation costs. These scenarios would result in total losses for these three crops of $25.4 million. By crop, the reductions in total net revenues corresponding to the most likely scenarios discussed above are $17.9 million for broccoli, $2.4 million for cabbage, and $5.1 million for onion.

Data availability was an important limitation for the scope of this analysis. Owing to the lack of data, some crops using dacthal are omitted and projected losses cannot be compared across crops (comparisons can be made across crops with the same sets of price, cost, and yield information). Other caveats to the analysis include the assumptions that: farmgate prices for the commodities are assumed perfectly elastic (i.e., changes in production costs as a result of dacthal deactivation do not affect the prices paid for the crop), one alternative herbicide would be used as an alternative AI, and no additional applications would be required. Our analysis does not account for other potential indirect costs of dacthal deactivation, such as limitations on crop rotations resulting from alternative herbicides and future changes in labor markets, which would increase the cost of labor-intensive activities such as hand weeding.

Introduction

A formal review of dacthal (aka chlorthal-dimethyl and DCPA) has been initiated as required by the Pesticide Contamination Prevention Act due to the detection of its degradates in groundwater. The purpose of the formal review process is to determine whether dacthal can continue to be used and, if so, under what conditions. In this report we evaluate the potential economic impacts to crops that are significant users of dacthal if the outcome of DPR's 2018 review process results in deregistration of dacthal. This report is part of the interagency consultation between the California Department of Pesticide Regulation (DPR) and the Office of Pesticide Consultation and Analysis (OPCA) in the California Department of Food and Agriculture (CDFA). Accordingly, the analysis is limited to OPCA's mandate, which is to evaluate the economic effects of regulations regarding pesticides being considered by DPR.[1]

The report focuses on brassica and allium crops, which together account for the majority of dacthal use as defined by either acres treated, or pounds of active ingredient applied. Broccoli alone accounted for 40 percent 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 percent of treated acreage.

In addition to evaluating statewide impacts, we also consider the use of dacthal in Monterey, San Luis Obispo, and Santa Barbara counties specifically. This is due to the high detections of dacthal degradates in well water in parts of these counties. Monterey County 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 ten percent of pounds applied and eight percent of acres treated.

The report is organized as follows. Background information regarding the detection of dacthal degradates in groundwater and the regulatory process is provided prior to a discussion of major uses of dacthal statewide and in the three counties. The study methodology is then presented, followed by an analysis of 2014-2016 herbicide use on crops using dacthal. The report then turns to an overview of weed management in an IPM program. Herbicide alternatives to dacthal are evaluated, then one alternative per crop is selected for the economic analysis. The components of the economic analysis are then presented individually. The herbicide material cost per acre is calculated using price and application rate information for dacthal and selected alternatives. Application costs are then addressed. Weeding costs are presented, followed by yield losses and gross revenue losses per acre. The preceding components are then combined to determine net revenue losses per acre. Finally, net revenue losses per acre are combined with information on acres treated with dacthal to calculate losses at the state and county levels for selected crops.

[1] California Food & Agricultural Code, Section 11454.2.

Background

Dacthal is a selective pre-emergence herbicide used for controlling annual grasses and certain broadleaved weeds. In California, agricultural uses are primarily for vegetable crops, though dacthal is also registered for use in turf, ornamentals, and strawberries. Dacthal was originally registered in 1958 when regulatory costs were much cheaper and the registration process much simpler than today. Currently (as of 08/07/18), there is one actively registered dacthal product (Dacthal Flowable Herbicide) in the DPR Product/Label database. Other products have had active registrations in California (e.g. Dacthal W-75) but are no longer active.

The dacthal mechanism of action is inhibition of mitosis by interference with microtubule formation, i.e., the microtubules do not line up properly and the cell cannot divide. Dacthal is a pre-emergence herbicide that controls susceptible weed seedlings during germination but is not active on emerged weeds. Susceptible weeds do not emerge because dacthal inhibits germination and meristem growth (Shaner et al. 2014). Dacthal is most active on certain small seeded broadleaf weeds like common lambsquarters and common purslane as well as grasses. Weeds in the mustard family are not susceptible to control by dacthal, which stands to reason as this herbicide is used in mustard green crops and closely related cruciferous vegetables like bok choy and radish (AMVAC Chemical Corporation 2015).

Dacthal is a niche herbicide used in crops with few alternative herbicides that have similar selectivity and efficacy as dacthal. For example, in direct-seeded dry bulb onion dacthal is the most selective herbicide available for use on sensitive young onion seedlings, and there is no obvious alternative. In crops like radish, gai lon and bok choy, i.e., the minor brassicas, there are no alternatives to dacthal because these niche crops have no registered replacement for dacthal. For crops like broccoli and cauliflower, the situation is somewhat better than the minor brassicas. Dacthal is important in seeded broccoli due to its excellent crop safety in seedling broccoli. However, broccoli is increasingly transplanted and transplanted broccoli has oxyfluorfen as an option. Additionally, seeded and transplanted broccoli also has the option of post-emergence applications of the oxyfluorfen product, GoalTender, which is labelled for pre-transplant and post-emergence use on broccoli and cauliflower.

Though dacthal tends to be relatively immobile in the soil, the degradates monomethyl tetrachloroterephthalic acid (MTP) and tetrachloroterephthalic acid (TPA) are more mobile and persistent (USEPA, 2008). In general, dacthal parent material is not very mobile in soil because it has low water solubility and a high soil adsorption coefficient. Dacthal is also moderately persistent with an aerobic soil metabolism half-life in the range of 17.7 to 38.8 days and a half-life ranging from 8 to 34.8 days. The metabolite MTP is mobile in soil due to its high water solubility (3,000 mg/L) and low soil adsorption coefficient (30 cm3/g). However, MTP is not persistent with an aerobic soil metabolism half-life of 2.8 days (Wettasinghe and Tinsley, 1993). The metabolite TPA is both mobile in soil, with high water solubility (5,780 mg/L) and negligible soil adsorption potential, and persistent in soil, with an aerobic soil metabolism half-life of more than 300 days (Wettasinghe and Tinsley, 1993). Thus, TPA is more likely than MTP or the parent compound (dacthal) to leach into groundwater.

The label for Dacthal Flowable Herbicide acknowledges the potential for TPA leaching by advising against applications to well-drained sand and loamy sand soils with high water tables. The label also indicates a potential for surface water contamination via spray drift and advises against applications in wet and/or poorly drained areas. Additionally, for most uses, applications in California must be banded. While the label addresses leaching, neither dacthal nor its degradates are currently listed on DPR's groundwater protection list (California Code of Regulations, 2014).

Dacthal use and Groundwater Protection Areas

DPR's Groundwater protection areas (GWPAs) place restrictions on the use of certain labile and persistent pesticides that are prone to move into groundwater. Based on a recent DPR report (Ruud, 2018) the highest well detections of TPA do not occur in existing DPR designated GWPAs nor the proposed additions to the GWPAs (CDPR 2017).

Figure 1 maps long-term dacthal use, GWPAs, and detections of dacthal degrades in groundwater in the Santa Maria area. As seen in the figure, GWPAs stop at the border of San Luis Obispo and Santa Barbara Counties demarcated by the Santa Maria River, but 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. Groundwater well samples have been found to contain dacthal degradates greater than the lifetime Health Advisory Level (HAL) of 70 ppb for dacthal and its degradates by the US EPA and adopted by DPR for its degradates (Ruud, 2018). Similarly, in the Salinas Valley high TPA detections are located in areas outside of GWPAs (Figure 2), specifically near the community of Greenfield (Ruud, 2018).

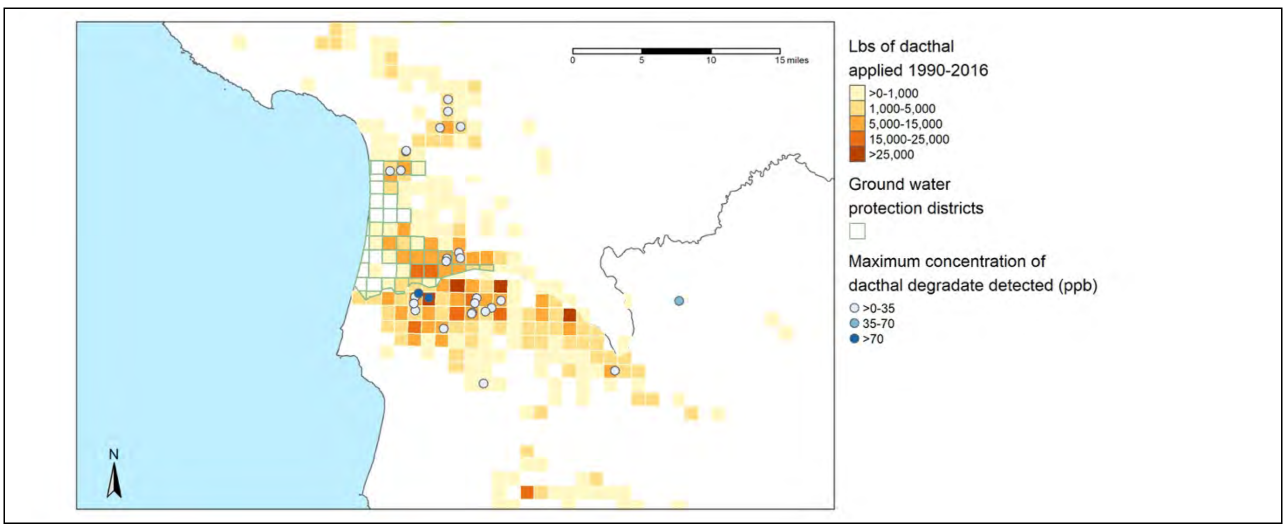


Figure 1. Long-term Dacthal Use Trends, Groundwater Protection Areas and Detections of Dacthal Degradates in Groundwater in the Santa Maria Area*

*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.

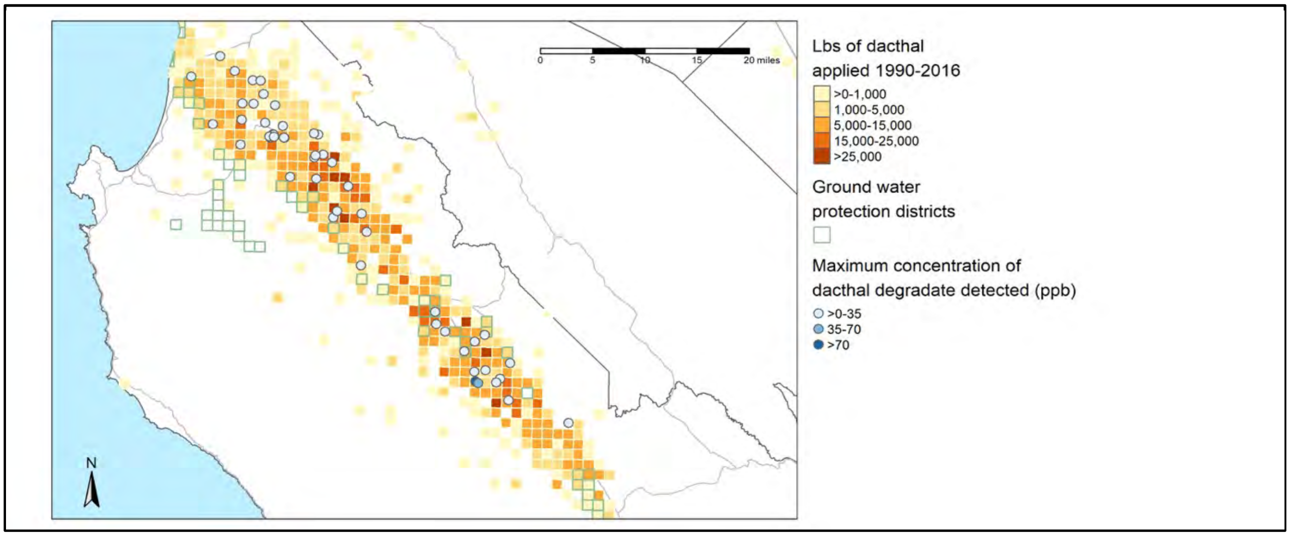


Figure 2. Long-term Dacthal Use Trends, Groundwater Protection Areas and Detections of Dacthal Degradates in Groundwater in the Salinas Valley Area*

*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.

Regulatory process

Dacthal degradation products monomethyl tetrachloroterephthalate (MTP) and 2,3,5,6-tetrachloroterephthalic acid (TPA) were detected in groundwater samples from a number of California counties (Lohstroh and Koshlukova, 2017; CDPR, 2016a; CDPR, 2016b; CDPR 2015). Under the 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 formal review process. The purpose of the formal review process is to determine whether or not the pesticide can continue to be used and, if so, under what conditions.

The formal review process occurs in three steps. First, DPR notifies the product registrant with a formal notice. Product registration will be cancelled unless the product registrant requests a public hearing and provides, for public comment, the requisite report and documentation as dictated by Food and Agriculture Code 13150. Second, if the aforementioned requirements are sufficiently satisfied, a public hearing before the DPR's Pesticide Registration and Evaluation Committee subcommittee is scheduled. The subcommittee is composed from one member of each of the following: DPR, Office of Environmental Health Hazard Assessment (OEHHA), and State Water Resources Control Board (SWRCB). Third, within 30 days after the public hearing, the subcommittee will meet to deliberate on a recommendation to the DPR Director. This meeting is open to the public, but not for public comment; information from DPR, OEHHA, and SWRCB can also be presented to the subcommittee. As per Food and Agriculture Code 13150(c), there are three possible recommendations:

(1) *That the ingredient found in the soil or groundwater has not polluted, and does not threaten to pollute, the groundwater of the state.*

(2) That the agricultural use of the pesticide can be modified so that there is a high probability that the pesticide would not pollute the groundwater of the state.

(3) That modification of the agricultural use of the pesticide pursuant to paragraph (2) or cancellation of the pesticide will cause severe economic hardship on the state's agricultural industry, and that no alternative products or practices can be effectively used so that there is a high probability that pollution of the groundwater of the state will not occur. The subcommittee shall recommend a level of the pesticide that does not significantly diminish the margin of safety recognized by the subcommittee to not cause adverse health effects.

When the subcommittee makes a finding pursuant to paragraph (2) or this paragraph (3), it shall determine whether the adverse health effects of the pesticide are carcinogenic, mutagenic, teratogenic, or neurotoxic.

Under Food and Agriculture Code 13150(d), the DPR director can respond in four possible ways to the recommendation:

(1) Concurs with the subcommittee finding pursuant to paragraph (1) of subdivision (c).

Concurs with the subcommittee finding pursuant to paragraph (2) of subdivision (c), and adopts modifications that result in a high probability that the pesticide would not pollute the groundwaters of the state.

(2) Concurs with the subcommittee findings pursuant to paragraph (3) of subdivision (c), or determines that the subcommittee finding pursuant to paragraph (2) of subdivision (c) will cause severe economic hardship on the state's agricultural industry. In either case, the director shall adopt the subcommittee's recommended level or shall establish a different level, provided the level does not significantly diminish the margin of safety to not cause adverse health effects.

(3) Determines that, contrary to the finding of the subcommittee, no pollution or threat to pollution exists. The director shall state the reasons for his or her decisions in writing at the time any action is taken, specifying any differences with the subcommittee's findings and recommendations. The written statement shall be transmitted to the appropriate committees of the Senate and Assembly, the State Department of Health Services, and the board.

When the director takes action pursuant to paragraph (2) or (3), he or she shall determine whether the adverse health effects of the pesticide are carcinogenic, mutagenic, teratogenic, or neurotoxic.

DPR issued a notice to the product registrant for dacthal, AMVAC Corporation, on March 7, 2018. The determination that the detections arose from legal agricultural use, the formal notice of detection letter (and three accompanying attachments), the product registrant's request for a public hearing, and further details are publicly available on the DPR's website.[2] The public hearing is scheduled for August 29, 2018.

[2] See: https://www.cdpr.ca.gov/docs/emon/grndwtr/chlorthal_dimethyl/chlorthal_dimethyl.htm.

Dacthal Use

Dacthal use in California declined significantly in the 1990s and has remained at relatively low levels since then (Figure 3). The removal of dacthal from the market in 1998 to 2001 appeared to reduce demand and set a low baseline demand for the product in the 2000's compared to 1993. Additionally, the registration of GoalTender, an oxyfluorfen-based product, as a post-emergence treatment for broccoli and cauliflower in 2006 greatly reduced the need for dacthal in these two crops (Dow AgroSciences 2006). Between 2014-2016, oxyfluorfen accounted for a majority of acres treated for broccoli and cauliflower with an herbicide AI (DPR Pesticide Use Reporting data, various years). The decline in dacthal use also was driven by changes in planting techniques of cole crops from direct seeded to greater use of transplants, which enables the use of oxyfluorfen-based products. Broccoli is established from seed and transplants, while cauliflower is established only from transplants. GoalTender is registered for use before transplanting in both broccoli and cauliflower (Dow AgroSciences 2014a).

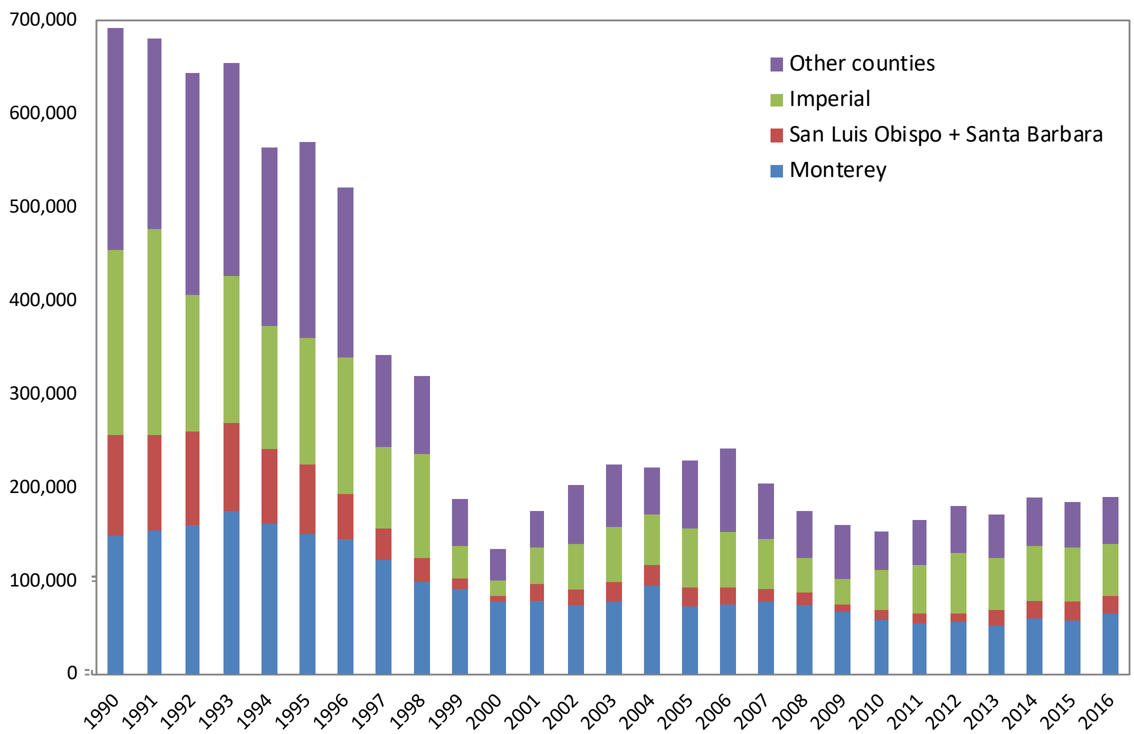


Figure 3. Dacthal Pounds of Active Ingredient Applied: 1990-2016

Statewide

Primary use of dacthal herbicide in California is in cole crops: broccoli, Brussels sprout, cabbage, cauliflower, kale, and kohlrabi (Table 1). Other cruciferous vegetables plantings that use dacthal include Chinese cabbage, bok choy, gai lon (Chinese broccoli), radish, kale, rapini, mustard and turnip. As noted above, dacthal is an important herbicide among the allium group of vegetables such as dry bulb onion, green onion and leek. Bulb onion is planted by direct seeding throughout

California. Onions seedlings are slow to emerge and grow thus are delicate and susceptible to herbicide injury.

Table 1. Dacthal Use by Pounds Active Ingredient Applied and Acres Treated: 2014-2016

Crop	Pounds AI Applied			Acres Treated		
	2014	2015	2016	2014	2015	2016
Broccoli	83,326	73,867	66,794	23,746	20,026	20,520
Onion, Dry	41,086	49,822	51,525	7,980	8,841	8,861
Cabbage	10,349	7,672	11,377	2,451	1,915	2,727
Cauliflower	8,402	7,042	8,578	2,671	2,358	3,001
Chinese Cabbage	7,031	8,066	6,996	1,607	1,616	1,483
Bok Choy	6,706	4,820	7,179	1,605	1,060	1,546
Brussels Sprout	4,693	3,757	8,934	871	669	2,115
Radish	5,219	4,388	5,449	914	848	996
N-Outdr Flower	3,315	4,059	3,697	620	740	670
Kale	2,518	3,377	4,875	451	579	807
Rapini	3,106	3,276	3,001	1,336	1,428	1,283
Mustard	1,658	3,299	2,919	592	496	473
Leek	1,193	1,867	2,448	231	324	399
Gai Lon	2,626	940	1,130	543	218	251
Kohlrabi	258	3,072	416	55	674	85
N-Outdr Plants in Containers	530	1,321	1,823	57	138	229
Onion, Green	2,071	541	168	329	100	28
Soil Fumigation/ Preplant	2,461	93		653	52	
Turnip	1,148	799	388	272	80	101
Uncultivated Ag	388	592	268	177	205	151
Others	1,178	1,400	974	296	243	182
Total	189,470	184,280	189,572	47,490	42,642	46,008

Source: Pesticide Use Reports data (CDPR).

Table 2 reports dacthal use by county for 2014-2016 for the top ten counties with the largest use, defined as the total pounds of active ingredient applied over the three-year period. Monterey, Santa Barbara, and San Luis Obispo counties are included. Due to the high detection levels of dacthal degradants, we also report use in those three counties individually.

Table 2. Dacthal Use by County: 2014-2016

County	Pounds AI Applied			Acres Treated		
	2014	2015	2016	2014	2015	2016
Monterey	60,945	58,676	65,770	21,909	19,681	22,400
Imperial	57,969	57,667	55,836	10,548	10,331	9,990
Fresno	18,340	21,421	15,071	3,043	3,031	2,105
Ventura	13,338	14,408	12,407	2,786	2,392	2,173
Santa Barbara	8,564	12,376	11,285	1,950	2,729	2,495
San Luis Obispo	9,808	6,838	7,361	1,964	1,122	1,408
Riverside	3,291	2,807	6,937	1,086	866	1,479
San Bernardino	5,670	2,094	2,579	1,301	518	614
San Benito	3,183	3,006	2,955	862	644	941
Kern	4,299	1,078	3,458	757	346	744
Others (14)	4,064	3,908	5,914	1,284	982	1,660
Total	189,470	184,280	189,572	47,490	42,642	46,008

Source: Pesticide Use Reports data.

Monterey County

Table 3 reports the treated and total acreage of dacthal treatments in Monterey County by crop and year from 2014-2016. Broccoli had the largest treated acreage and total harvested acreage in all three years. Cauliflower and onions alternated for the second and third-highest treated acreage during 2014-2016: onions were second-highest and cauliflower third-highest for 2014 and 2015, whereas in 2016 cauliflower was second and onions third. Treated acreage for broccoli was roughly an order of magnitude larger (over 14,000 acres each year) than onion and cauliflower treated acreage (roughly 2,000 acres each year). The fourth largest crop, cabbage, was another order of magnitude smaller than cauliflower and onions, with annual treated acreage of 458, 495, and 648 acres from 2014-2016, respectively. The remaining crops had relatively small treated acreages in spite of large total acreage.

Between 2014-2016, treated acreage appeared to increase over time for Brussels sprouts, kale, leek and radish. In contrast, treated acreage was relatively flat for bok choy, broccoli, cabbage, cauliflower, Chinese cabbage, kohlrabi, onions, and green onions.

Table 3. Dacthal Treatments in Monterey County by Crop and Year: 2014-2016

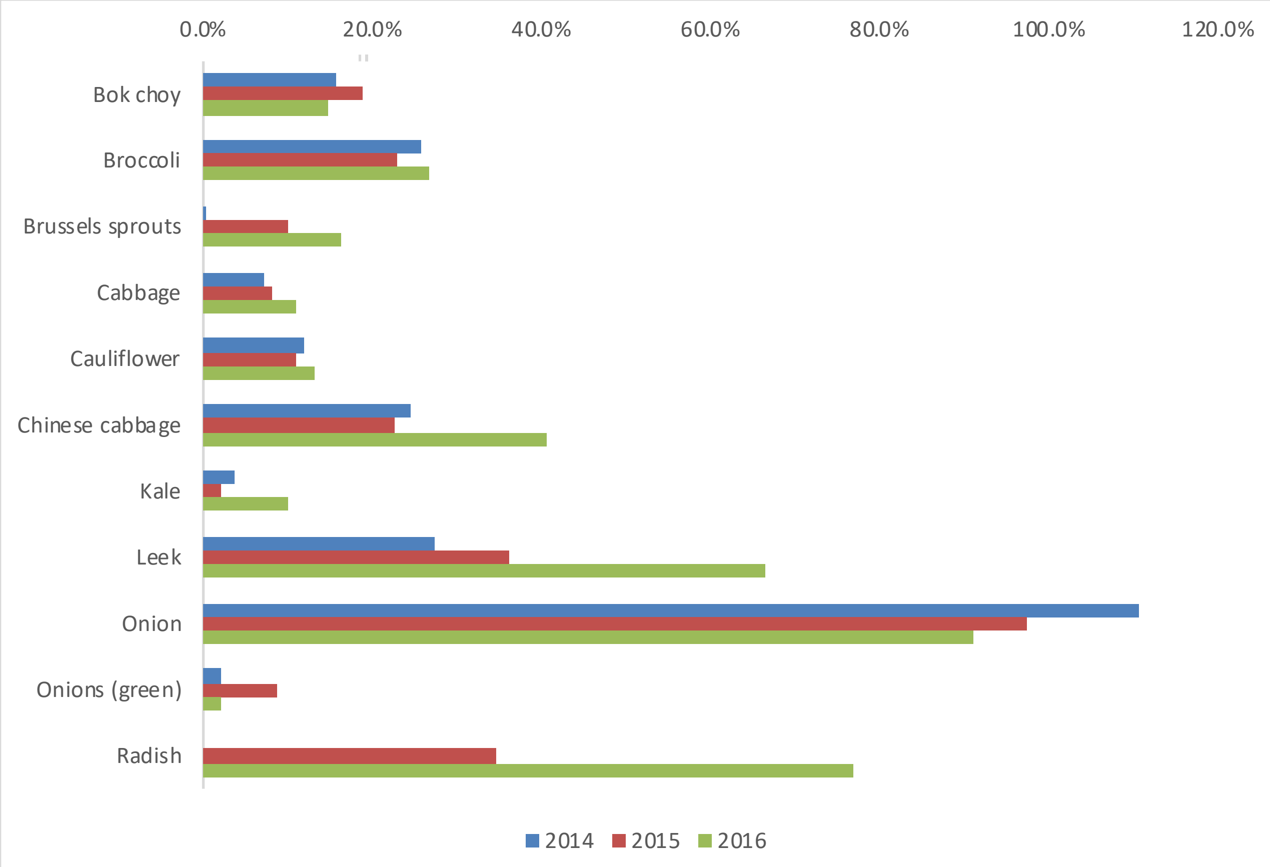
	2014		2015		2016	
Crop	**Treated**	**Total**	**Treated**	**Total**	**Treated**	**Total**
Bok choy	65	411	80	422	75	506
Broccoli	16,333	63,651	14,087	61,697	15,324	57,566
Brussels sprout	81	--	186	1,835	520	3,216
Cabbage	458	6,297	495	6,035	648	5,869
Cauliflower	2,069	17,566	2,061	18,655	2,802	21,033
Chinese cabbage	135	550	123	541	193	474
Kale	94	2,553	51	2,534	266	2,694
Kohlrabi	0	--	11	--	21	--
Leek	90	329	121	334	226	339
Mustard, curled	5	--	--	--	72	
Onion	2,077	1,875	2,235	2,296	2,011	2,205
Onions (green)	21	1,005	87	992	18	911
Radish	--	--	49	141	126	164
Seedbeds, etc.	342	--	--	--	--	--

Source: Treated from Pesticide Use Reports data and total from harvested acreage from Monterey County Crop Reports (2014-2016). Harvested acreage data for Brussels sprout was not reported in 2014. Harvested acreage data for Kohlrabi was not reported in 2016.

To capture the overall use of dacthal in each crop, treated acreage as a share of total harvested acreage treated with dacthal is reported for each crop and year in Figure 4. It is important to note there can be multiple applications of dacthal on a given crop, thus a treated field (and its acreage) can be counted multiple times, and that more than one production cycle can occur in a year for some crops. As a result, the treated acreage can exceed total acreage—indicative of the importance of dacthal to the crop. The treated share exceeded 100 percent for onions in 2014 and the share exceeded 90 percent in 2015 and 2016, suggesting dacthal was quite important for onion production. The next three pronounced crops in the figure are Chinese cabbage, leek, and radish, though it should be noted that acreage in these crops was relatively small. Recall from Table 3 that broccoli had the greatest treated and total acreage, and its share exceeded 20 percent in all three years. Finally, two other crops, cauliflower and cabbage, also had fairly large shares of around 10 percent.

Most of the crops accounting for acreage treated with dacthal in Monterey County were brassica and allium crops. The only other crop was radish, which has relatively few treated acres.

Figure 4. Monterey County Dacthal Treatments as Share of Total Acreage, by Crop and Year, 2014-2016



Source: Treated and percentage from Pesticide Use Report data and authors' calculations, and total from harvested acreage from Monterey County Crop Reports (2014-2016).

Santa Barbara County

Table 4 reports the treated and total acreage of dacthal treatments in Santa Barbara County by crop and year from 2014-2016. The highest treated acreage changes each year were: broccoli in 2014, kohlrabi in 2015, and Brussels sprout in 2016. Treated acreage exceeded 300 each year only for outdoor cut flowers, 200 acres each year for Chinese cabbage, and 100 acres each year for Brussels sprouts. Bok choy and broccoli both had two years where treated acreage exceeded 200; cauliflower, kale, and outdoor potted plants had two years where treated acreage exceeded 100. Aside from kale and kohlrabi in 2015, the remaining crops—cabbage, leek, mustard greens, onions, radish, tomato, and turnip—had relatively small treated acreages.

Santa Barbara County reported total acreage for the majority of crops in Table 4 in a "Miscellaneous Vegetables" category. In 2016, "Miscellaneous Vegetables" included bok choy, Brussels sprout, Chinese cabbage, kale, kohlrabi, leek, mustard greens, onions (dry and green), radish, tomato, and turnip, amongst other crops. As a result, we can compare treated and harvested acreage for only a few crops: broccoli, cabbage, cauliflower, and the outdoor flowers (cut and potted). For broccoli, the treated share steadily trended downwards from 2.0 percent in 2014, to 0.9 percent in 2015, and 0.3 percent in 2016. Treated share for cauliflower similarly trended downwards, from 1.4 percent in 2014, to 1.3 percent in 2015, and less than 0.05 percent in 2016. In contrast, treated acreage trended upwards for outdoor cut flowers and potted plants: 48.5 percent in 2014, 60.2 percent in 2015, and 58.2 percent in 2016 for the former, 11.2 percent in 2014, 32.1 percent, and 49.3 percent in 2016 in the latter. Again, note that there can be multiple applications of dacthal on a given crop, thus a treated field (and its acreage) can be counted multiple times, and as a result the treated acreage can exceed total acreage; however, this remains indicative of the importance of dacthal to the crop. For reference, the total acreage of the "Miscellaneous Vegetables" category was 11,939 in 2014, 12,012 in 2015, and 12,252 in 2016.

Similar to our earlier findings, dacthal was most important to cole crops in Santa Barbara. Onions and leeks also received treatments during the sample period. Similar to Monterey County, radish had very low treated acreage.

Table 4. Dacthal Treatments in Santa Barbara County, by Crop and Year, 2014-2016

	2014		2015		2016	
Crop	**Treated**	**Total**	**Treated**	**Total**	**Treated**	**Total**
Bok choy	87	--	247	--	302	--
Broccoli	550	27,371	230	26,276	74	24,969
Brussels sprout	341	--	126	--	812	--
Cabbage	--	1,143	--	1,257	--	1,319
Cauliflower	114	8,148	113	8,630	4	8,285
Chinese cabbage	214	--	502	--	367	--
Kale	50	--	114	--	139	--
Kohlrabi	50	--	658	--	57	--
Leek	--	--	7	--	21	--
Mustard greens	18	--	15	--	--	--
Onion	--	--	1	--	1	--
Onions (green)	--	--	--	--	--	--
Radish	1	--	1	--	0	--
Tomato	--	--	--	--	2	--
Turnip	--	--	--	--	31	--
N-Outdoor Flowers	467	963	580	963	498	856
N-Outdoor Plants in Containers	47	421	130	405	189	383

Sources: Treated from Pesticide Use Report data and total from harvested acreage from Santa Barbara County Crop Reports (2014—2016).

San Luis Obispo County

Table 5 reports the treated and total acreage of dacthal treatments in San Luis Obispo County by crop and year from 2014-2016. Chinese (Nappa) cabbage had the largest treated acreage in all three years, exceeding 600 treated acres every year, despite having only the third-largest non-missing total acreage in 2014 when total acreage was reported separately. Brussels sprout in 2016 was the only other crop to exceed 500 treated acres in any year. While bok choy and Brussels sprout were consistently near or above 200 treated acres, cauliflower and broccoli treated acreage was near or above 200 acres once, in 2014. The remaining crops—kale, kohlrabi, leek, mustard greens, onions, radish, tomato, and outdoor flowers (cut and potted)—had relatively few treated acres, never exceeding 75 treated acres and exceeding 50 treated acres only four times. Between 2014-2016, treated acreage was perhaps increasing only for Brussels sprout, relatively constant for other crops (notably bok choy), and decreasing for broccoli, cabbage, and Chinese cabbage.

San Luis Obispo County reported total acreage for the majority of crops in Table 5 in a "Miscellaneous Vegetables" category. In 2016, "Miscellaneous Vegetables" included bok choy, Brussels sprout, cabbage, cauliflower, Chinese cabbage, kale, kohlrabi, leek, mustard greens, onions (dry and green), radish, and tomatoes, amongst other crops. As a result, we can meaningfully use treated acreage as a share of total acreage to capture the importance of dacthal for only broccoli and cauliflower. For broccoli, the treated share was 2.6 percent in 2014, 0.1 percent in 2015, and less than 0.05 percent in 2016. The treated share for cauliflower decreased from 11.5 percent in 2014 to zero in 2015. In 2014, we also have reported total acreage for Chinese cabbage and outdoor flowers. With 54.5 percent treated share in 2014, dacthal had relatively high use in Chinese cabbage. Outdoor cut flowers at 14.7 percent had higher dacthal use than outdoor potted plants. Note that there can be multiple applications of dacthal on a given crop, thus a treated field (and its acreage) can be counted multiple times, and as a result the treated acreage can exceed total acreage; however, this remains indicative of the importance of dacthal to the crop as discussed earlier. For reference, the total acreage of the "Miscellaneous Vegetables" category was 9,273 in 2014, 11,583 in 2015, and 12,981 in 2016.

Cole crops and outdoor plants showed the highest dacthal use in San Luis Obispo. Onions and leeks also received treatments during the sample period. Similar to Monterey and Santa Barbara counties, radish had very low treated acreage.

Table 5. Dacthal Treatments in San Luis Obispo County, by Crop and Year, 2014-2016

	2014		2015		2016	
Crop	**Treated**	**Total**	**Treated**	**Total**	**Treated**	**Total**
Bok choy	185	--	218	--	189	--
Broccoli	252	9,878	5	7,398	2	8,089
Brussels sprout	248	--	126	--	531	--
Cabbage	51	720	62	--	6	--
Cauliflower	198	1,725	0	1,920	--	--
Chinese cabbage	856	1,571	627	--	633	--
Kale	75	--	48	--	27	--
Kohlrabi	0	--	0	--	--	--
Leek	15	--	32	--	17	--
Mustard greens	0	--	--	--	--	--
Onion	65	--	0	--	1	--
Onions (green)	--	--	--	--	--	--
Radish	1	--	1	--	0	--
Tomato	--	--	--	--	3	--
N-Outdoor Flowers	19	129	--	64	--	73
N-Outdoor Plants in Containers	0	233	--	208	--	224

Sources: Treated from Pesticide Use Report data and total from harvested acreage from San Luis Obispo County Crop Reports (2014—2016).

Frequency of dacthal applications

All else equal, fields with multiple applications of dacthal are more likely to contribute to groundwater leaching. Table 6 shows the number of dacthal applications to fields statewide for the years 2014–2016, where a field is defined as a unique combination of the *grower_id* and *site_loc_id* variables in the PUR dataset. If, for example, the grower grew broccoli followed by onions and applied dacthal once to each crop, this would be recorded in the table as two dacthal applications to the field that year. Seventy-eight percent of fields receiving dacthal had only one application of dacthal a year.

Table 6. Frequency of Dacthal Applications to Fields: 2014-2016, California

Number of Apps	2014	2015	2016
1	1,603	1,943	2,252
2	337	209	240
3	111	73	95
4	65	52	43
5+	145	115	117

Source: Authors' calculations derived from the CDPR Pesticide Use Report data.

As noted earlier, high concentrations of dacthal degradates have been detected in Monterey, Santa Barbara, and San Luis Obispo counties. All three counties have production systems that harvest more than one crop in a given calendar year. Table 7 reports the number of dacthal applications to fields in Monterey, Santa Barbara, and San Luis Obispo counties for 2014–2016. Most fields, 83 percent, had only one application of dacthal per year.

Table 7. Frequency of Dacthal Applications to Fields: 2014-2016, Monterey, Santa Barbara and San Luis Obispo Counties

	2014			2015			2016		
Number of Apps	**Mon.**	**SB**	**SLO**	**Mon.**	**SB**	**SLO**	**Mon.**	**SB**	**SLO**
1	1,265	28	72	1,612	31	50	1,935	27	43
2	217	20	45	84	15	48	117	22	47
3	53	11	26	11	12	15	23	10	26
4	23	2	18	5	11	11	5	12	9
5+	24	18	30	2	23	23	2	23	15

Source: Authors' calculations derived from the CDPR Pesticide Use Report data.

Of the three counties, Monterey had the most dacthal applications over the three years, with the majority of fields receiving only a single treatment of dacthal. The frequency of dacthal applications declined rapidly. An order of magnitude fewer fields received two dacthal treatments, and another order of magnitude fewer received three or more applications. This pattern was repeated across the three years. Additionally, the frequency of multiple treatments declined in Monterey County across the three years. Single treatments increased from 1,265 in 2014 to 1,935 in 2016 while double treatments declined from 217 to 117. The number of fields receiving four treatments declined from 23 in 2014 to five in 2016, and the number of fields receiving five or more treatments had a similar reduction. This decline may have been influenced by a change in crop mix or a change in the weed management program for a given crop mix.

Santa Barbara and San Luis Obispo counties had far fewer dacthal applications overall, with less clear trends. It was still most common for fields to only receive a single application of dacthal and there was a rough reduction in frequency as the number of applications per field increased. Strikingly, these two counties had a relatively large number of fields receiving five or more dacthal applications, primarily due to flowers and other crops with relatively short production cycles. In 2015 and 2016 the frequency of fields receiving five or more applications was an order or magnitude larger than in Monterey County.

Tank mixes

Pesticides are frequently applied in "tank mixes," where several products are mixed together and applied to the field in a single application. The products used in the mix depend on the pest control needs of the grower. In this analysis, tank mixes were identified by grouping PUR entries with identical times and date of application, grower ID numbers, and field ID numbers. That is, we assume that the products used at the same time (including year), by the same grower, on the same field, were applied in a single mixture.

If dacthal is used with other, non-herbicide products, switching from dacthal to another herbicide that can also be applied with those products may not change the total number of applications the grower makes and hence will not change application costs. On the other hand, dacthal may be mixed with other herbicides because of the spectrum of control provided by the combination. If dacthal were not available, the grower may need to change control strategies, possibly requiring additional pesticide applications and incurring additional fixed costs.

Table 8 reports the product types present in mixes used statewide in 2014 to 2016. For each year, insecticides were the most common co-product, followed by adjuvants (chemicals applied to improve the effectiveness of another pesticide), herbicides, and fungicides. Relatively few dacthal applications were accompanied by another herbicide in the tank mix. Statewide, dacthal was applied with at least one other herbicide in approximately 16 percent of applications (with year-to-year variation of around one percent). The most popular herbicide AI used with dacthal was bensulide, which was used in over half of tank mixes including at least one other herbicide in addition to dacthal. Napropamide and oxyfluorfen were the next most popular herbicides.

Table 8. Frequency of Product Types Used in Mixes with Dacthal: 2014-2016, California

Type Name	2014	2015	2016
Adjuvant	1190	918	1576
Algaecide	1	0	0
Anti-Microbial	7	22	1
Bactericide	8	47	24
Defoliant	21	1	7
Desiccant	21	1	7
Fungicide	297	280	338
Herbicide	**756**	**643**	**897**
Insect growth regulator	0	1	0
Insecticide	2693	2320	2506
Miticide	4	132	137
Molluscicide	2	0	0
Nematicide	57	115	204

Source: Authors' calculations derived from the CDPR Pesticide Use Report data.

Table 9 reports the product types present in mixes with dacthal in Monterey, Santa Barbara, and San Luis Obispo counties in 2014 to 2016. For all three years in Monterey County, insecticides were most commonly used in mixes with dacthal, followed by adjuvants and other herbicides. San Luis Obispo County had a similar pattern. In Santa Barbara, however, herbicides were often the second most frequent product type used with dacthal. Other commonly used pesticide types include fungicide in Santa Barbara in 2015, and Monterey and Santa Barbara in 2016, nematicides each year in Santa Barbara and San Luis Obispo counties, and miticides in Monterey in 2015 and 2016.

As was the case statewide, relatively few dacthal applications were accompanied by another herbicide in the tank mix. In Monterey County, around 11 percent of dacthal applications included at least one other herbicide. San Luis Obispo County had more variation across years, with 24 percent of dacthal applications including at least one other herbicide in 2014, 12 percent in 2015, and 23 percent in 2015. Of the three counties, Santa Barbara had the highest proportion of dacthal applications including at least one other herbicide, with 24 percent in 2014, and 38 percent in 2015 and 2016.

In Monterey County, the most popular herbicide AIs used with dacthal were bensulide, napropamide, and pendimethalin. In San Luis Obispo County, the most popular herbicide AIs used with dacthal were napropamide, bensulide, and oxyfluorfen. In Santa Barbara County, the most popular herbicide AIs used with dacthal were bensulide, napropamide, and trifluralin.

Table 9. Frequency of Product Types Used in Mixes with Dacthal by County and Year: 2014-2016, Monterey, Santa Barbara and San Luis Obispo Counties

	2014			2015			2016		
Type Name	**Mon.**	**SB**	**SLO**	**Mon.**	**SB**	**SLO**	**Mon.**	**SB**	**SLO**
Adjuvant	558	19	155	290	16	75	838	14	118
Algaecide		1							
Bactericide				1	4			4	3
Defoliant	1	1	16						2
Desiccant	1	1	16						2
Fungicide		6	10	1	75		23	103	6
Herbicide	259	87	185	222	183	49	245	210	98
Insect growth regulator					1				
Insecticide	1,648	131	377	1,391	136	292	1,557	139	351
Miticide	1			60		1	68		
Nematicide		36	19	1	91	23		162	42

Source: Authors' calculations derived from the CDPR Pesticide Use Report data.

Table 10 shows the top ten most common tank mixes containing dacthal by area in Monterey County for 2014 to 2016. The first row shows statistics for dacthal applied unaccompanied, i.e., not as part of a mix. The remaining rows show the products used in mixtures with dacthal. Each year the most frequent mix was dacthal alone, accounting for approximately one quarter of applications containing dacthal. Bifenthrin, clothianidin, cypermethrin, esfenvalerate, and spinosad, all insecticides, were common components of mixes. Herbicides identified as potential partial replacements for dacthal are in boldface type. Only bensulide and napropamide were used in the most common mixes. The combination of the two herbicides indicates that their spectrums of control differ. Tank mixes containing an additional herbicide product were used on fewer than four percent of treated acres.

Table 10. Common Tank Mixes in Monterey County: 2014-2016

AIs in Mix with dacthal	2014 Acre	2014 Freq.	2015 Acre	2015 Freq.	2016 Acre	2016 Freq.
Dacthal Only	6,090	595	4,591	573	8,672	924
Clothianidin	4,747	381	5,689	446	3,683	322
(S)-Cypermethrin	2,355	284	2,152	228	1,781	242
Spinosad	983	95				
(S)-Cypermethrin, Clothianidin	869	58	1,352	97	1,322	98
Bifenthrin	763	66	937	67	628	62
Bensulide	756	62	987	90	539	48
Esfenvalerate	667	81	369	42	310	32
(S)-Cypermethrin, Imidacloprid	581	56	459	53	542	74
Beta-Cyfluthrin, Imidacloprid	514	53				
Lambda-Cyhalothrin			555	32	618	45
Bensulide, Clothianidin			384	33		
Napropamide					316	27
Other	3,449	317	2,137	201	3,896	397
Total	21,773	2,048	19,612	1,862	22,307	2,271

Source: Authors' calculations derived from the CDPR Pesticide Use Report data. Note: Herbicides identified as potential partial replacements for dacthal are in boldface type.

Table 11 shows the ten most common tank mixes containing dacthal by acres treated in Santa Barbara County for 2014 to 2016. In 2014 the most frequently applied mix was dacthal alone. In 2015 and 2016, (S)-cypermethrin was the AI most commonly mixed with dacthal, accounting for around 30–35 percent of acres treated with any dacthal. A substantial share of applications and acreage for tank mix applications included at least one additional herbicide, which was likely included to control a broader range of weed species. Santa Barbara County displayed greater year-to-year variation than Monterey in the tank mixes used. Only five mixes appeared in the top-ten most common mixtures each year.

Table 11. Common Tank Mixes in Santa Barbara County: 2014-2016

AIs in Mix with Dacthal	2014 Acre	2014 Freq.	2015 Acre	2015 Freq.	2016 Acre	2016 Freq.
Dacthal Only	318	150	216	134	109	64
Napropamide, Oxyfluorfen	294	34				
Imidacloprid	285	83	65	20	96	28
Lambda-Cyhalothrin	265	55				
(S)-Cypermethrin	171	47	332	84	489	102
Clothianidin, **Napropamide, Oxyfluorfen**	84	11				
Imidacloprid, Myrothecium Verrucaria, Dried Fermentation Solids & Solubles, Strain AARC-0255	71	12	97	18	132	23
Dimethenamid-P, Lambda-Cyhalothrin, Pyrimethanil	65	9				
Imidacloprid, **Napropamide**	64	10	85	10	316	40
Imidacloprid, Lambda-Cyhalothrin	40	6				
Cypermethrin			123	25		
Imidacloprid, **Oxyfluorfen**			17	8		
Clothianidin, Imidacloprid, **Napropamide**			16	2		
Chlorantraniliprole, Thiamethoxam			16	24		
Bensulide, Imidacloprid			14	6	23	10
Glyphosate, Isopropylamine Salt, Imidacloprid, **Napropamide**					89	13
Imidacloprid, Myrothecium Verrucaria, Dried Fermentation Solids & Solubles, Strain AARC-0255, **Napropamide**					49	11
Myrothecium Verrucaria, Dried Fermentation Solids & Solubles, Strain AARC-0255					20	5
(S)-Cypermethrin, Imidacloprid					19	36
Other	303	106	129	54	58	26
Total	1,960	523	1,110	385	1,399	358

Source: Authors' calculations derived from the CDPR Pesticide Use Report data Note: Herbicides identified as potential partial replacements for dacthal are in boldface type.

Table 12 shows the top ten most common tank mixes containing dacthal by area in San Luis Obispo County for 2014 to 2016. The most common mixture changed each year. In 2014 the most common mixture by area was dacthal alone, but this use decreased in 2015 and 2016. In 2015, the most common mixture was dacthal and bensulide, an herbicide, accounting for 29 percent of acres treated with any dacthal. In 2016, the most common mix was imidacloprid (an insecticide), myrothecium verrucaria, dried fermentation solids & solubles, strain AARC-0255 (a bio-pesticide for controlling nematodes and weeds), and napropamide (an herbicide). A substantial share of applications and acreage for tank mix applications included at least one additional herbicide, which was likely included to control a broader range of weed species.

Like Santa Barbara County, San Luis Obispo County displayed more year to year variation in the tank mixes used than Monterey County, with several mixes appearing in a single year only. For example, bensulide mixes became popular in 2015 and 2016.

Table 12. Common Tank Mixes in San Luis Obispo County: 2014-2016

	2014		2015		2016	
AIs in Mix with Dacthal	**Acre**	**Freq.**	**Acre**	**Freq.**	**Acre**	**Freq.**
Dacthal Only	627	167	538	115	377	172
Imidacloprid, **Napropamide**	448	33	165	15		
Imidacloprid	375	40	95	11	49	14
Imidacloprid, Myrothecium Verrucaria, Dried Fermentation Solids & Solubles, Strain AARC-0255	239	36	457	72	285	57
Napropamide	76	5	34	2		
Napropamide, Oxyfluorfen	75	7				
Bensulide, Imidacloprid	32	8				
Imidacloprid, **Trifluralin**	20	6				
Trifluralin	19	16				
Clothianidin, **Napropamide, Oxyfluorfen**	11	1				
Bensulide			789	138	343	109
Bacillus Amyloliquefaciens Strain D747			342	63	371	51
Myrothecium Verrucaria, Dried Fermentation Solids & Solubles, Strain AARC-0255			115	16	95	19
Imidacloprid, **Oxyfluorfen**			35	4		
Beta-Cyfluthrin, Imidacloprid, Permethrin			22	6		
Imidacloprid, Myrothecium Verrucaria, Dried Fermentation Solids & Solubles, Strain AARC-0255, **Napropamide**					704	50
Bacillus Amyloliquefaciens Strain D747, Streptomyces Lydicus Wyec 108					103	24
Bensulide, Clothianidin					59	7
Bensulide, Purpureocillium Lilaciunum Strain 251					44	34
Other	29	7	138	37	66	12
Total	1,950	326	2,729	479	2,495	549

Source: Authors' calculations derived from the CDPR Pesticide Use Report data. Note: Herbicides identified as potential partial replacements for dacthal are in boldface type.

Methods

Crops included in this study are brassica (mustard family) and allium (onion family) crops that currently use dacthal and would be impacted by the loss of this herbicide. Current use was defined as any reported use in the three-year period 2014 to 2016. 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. Crops excluded from analysis within the top twenty uses reported in Table 1 include radish, nursery-outdoor flower, nursery-outdoor plants in containers, and turnip. Other excluded PUR site names include preplant /soil fumigation and uncultivated agriculture.

The analysis follows the general approach presented in Steggall et al. (2018). Crop acreage data were obtained from the CDFA annual report and from county agricultural commissioner county crop reports. Pesticide use data were obtained from the PUR database. Specifically, we collect the amount of active ingredient and treated acreage from 2014 to 2016 from the PUR database for dacthal and all possible replacement herbicides. Product prices were collected from online retailers, or when that was not available, solicited from agricultural product vendors or manufacturers with the understanding that they would remain anonymous.

Our economic analysis uses a partial budgeting approach. We consider only changes in costs and revenues due to using an alternative control method instead of dacthal. We include an evaluation of current herbicide use followed by an assessment of potential alternatives to the use of dacthal, including alternative pesticide active ingredients and hand weeding. Not all potential pesticide alternatives are registered for all crops considered. None of the identified alternatives are direct replacements. Consequently, additional cultivation and/or hand-weeding would be required, increasing costs. Furthermore, yield losses may occur, reducing revenues. These factors are included when the available data permit. Based on the evaluation of potential herbicide alternatives, a single active ingredient is selected for each crop or group of crops. A representative product is then selected for each active ingredient in order to calculate the cost of the alternative.

Specifically, we separate the economic impact of a dacthal deregistration 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 in conducting this analysis 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. For example, the dacthal replacement may require an extra application, so the cost of replacing dacthal is not only the replacement materials, but also the additional cost of conducting an application. With respect to (iii), additional labor costs may be needed when the replacement herbicide does not provide complete control and must be augmented by hand-weeding. Note that the per acre hand-weeding costs can vary greatly based on the plant density and the plant itself; thus, we evaluate hand-weeding costs on a per crop basis as much as possible. Finally, to account for the fact that replacement herbicides may not provide complete 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.

Two other important challenges regarding this analysis concern data availability. First, due to small harvested acreage, not all of the affected crops have reported information regarding acreage, yield, and/or price. Second, crop-specific cost studies are not available for many of the crops. Another critical challenge is exacerbated by these data difficulties. Brassica crops are produced using a variety of cropping systems, and there are a large number of these crops. Consequently, it is difficult to generalize across them all. We provide estimates based on the information available, and do not extrapolate across crops.

Current Herbicide Use on Crops Using Dacthal

Dacthal plays an important role in weed management for a number of crops. Table 13 reports the most-used herbicide active ingredients based on 2014-2016 treated acreage for broccoli, other cole crops, dry onion, green onion, and leek. It also reports the share of those active ingredients in total acres treated and their most common product. Examining the table, dacthal accounted for an absolute majority (51+ percent) of treated acres for seven of the eighteen reported crops: Chinese cabbage, bok choy, radish, leek, gai lon, kohlrabi and mustard greens. It was the active ingredient with the largest treated acres for an additional four crops: Brussels sprout, rapini, green onion (tied with oxyfluorfen) and turnip. Dacthal ranked among the top active ingredients for all listed crops except dry onion, for which it ranked eighth.

This table illustrates the relative use of dacthal and other active ingredients, shown as percentages, across multiple years.[3] Two potentially relevant facts are not obvious in this presentation. First, green onion registered a substantial decline in acreage treated with any herbicide from 2014 to 2016. Second, all oxyfluorfen use in leeks was in 2014. The appendix includes detailed information on the herbicide active ingredients and products for all crops with any dacthal use for Monterey, Santa Barbara, and San Luis Obispo counties.

Table 13. Top Herbicide AIs by Acres 2014-2016, Percentages of All Herbicide-treated Acreage, and Main Product: Broccoli, Other Cole Crops, Dry Onion, Green Onion, and Leek.

Crop	Top 2-4 AIs	% of All Herbicide AIs	Example Product
Broccoli	Oxyfluorfen	49	GoalTender
	Dacthal	20	Dacthal Flowable
	Bensulide	8	Prefar 4-E
	Trifluralin	8	Triflurex/Trifluralin
Dry Onion	Oxyfluorfen	30	GoalTender
	Bromoxynil	21	Maestro 4EC/2EC
	Pendimethalin	16	Prowl H2O
	Dimethenamid-p	6	Outlook
Cabbage	Oxyfluorfen	51	GoalTender
	Dacthal	19	Dacthal Flowable
	Bensulide	10	Prefar 4-E
	Trifluralin	4	Triflurex/Trifluralin
Cauliflower	Oxyfluorfen	70	GoalTender/Goal 2XL
	Dacthal	9	Dacthal Flowable
	Napropamide	6	Devrinol DF-XT/50-DF

[3] The table also combines two pairs of products for ease of interpretation: Triflurex/Trifluralin references either Triflurex HFP or Trifluralin HF, and Devrinol DF-XT/50-DF references either Devrinol DF-XT or Devrinol 50-DF.

Crop	Top 2-4 AIs	% of All Herbicide AIs	Example Product
	Trifluralin	5	Triflurex/Trifluralin
Chinese Cabbage	Dacthal	64	Dacthal Flowable
	Bensulide	20	Prefar 4-E
	Trifluralin	6	Triflurex/Trifluralin
Bok Choy	Dacthal	70	Dacthal Flowable
	Bensulide	23	Prefar 4-E
	Trifluralin	6	Triflurex/Trifluralin
Brussels sprout	Dacthal	38	Dacthal Flowable
	Napropamide	26	Devrinol DF-XT/50-DF
	Bensulide	13	Prefar 4-E
	Oxyfluorfen	4	GoalTender
Kale	Bensulide	40	Prefar 4-E
	Dacthal	21	Dacthal Flowable
	Trifluralin	7	Triflurex/Trifluralin
	Clethodim	5	Select Max
Rapini	Dacthal	32	Dacthal Flowable
	Clethodim	24	Intensity
	Bensulide	22	Prefar 4-E
Mustard	Bensulide	34	Prefar 4-E
	Dacthal	33	Dacthal Flowable
	Trifluralin	29	Triflurex/Trifluralin
Leek	Dacthal	76	Dacthal Flowable
	Pendimethalin	18	Prowl H2O
	Oxyfluorfen	2	GoalTender
Gai lon	Dacthal	64	Dacthal Flowable
	Bensulide	23	Prefar 4-E
	Trifluralin	11	Triflurex/Trifluralin
Kohlrabi	Dacthal	51	Dacthal Flowable
	Bensulide	49	Prefar 4-E
Green Onion	Dacthal	22	Dacthal Flowable
	Oxyfluorfen	22	GoalTender
	Clethodim	16	Intensity / Clethodim 2E

Crop	Top 2-4 AIs	% of All Herbicide AIs	Example Product
	Bromoxynil	14	Maestro 2EC

+ Novaluron ranks third at 11%; listed as both an insecticide and herbicide in the PUR, but the main product (Rimon 0.83 EC) does not list weed control on the label; it may possibly also used as a burndown due to phytotoxicity
++ Potash soap ranks third for cauliflower at 6%; first for kale at 60%. It is listed as an insecticide and herbicide in the PUR; but the main product (M-pede) does not list weed control on the label. The UC IPM PMG for cole crops notes that insecticidal soap has phytotoxic properties under some conditions for cabbage and Brussels sprout, which would be consistent with possible use as a burndown.

Frequency of applications of multiple herbicides

Depending on the crop and local weed pressures, growers may use multiple herbicides to achieve an appropriate spectrum of control. Table 14 presents the number of distinct herbicide products growers statewide used on their fields in 2014–2016.[4]

Generally, most fields treated with any herbicide product were treated with only one. Fewer fields received a greater number of distinct herbicides; there were more fields and acreage treated with two products than with three, more treated with three than with four, and so on. The two notable exceptions were onions and nursery-outdoor flowers. The use of multiple distinct herbicides for onions is consistent with the UC IPM guidelines, which recommend different herbicides at different stages of the onion's life-cycle. Outdoor flower nurseries use a variety of distinct herbicides because they grow a variety of flowers and other crops with short production cycles.

Table 14. Number of Distinct Herbicide Products Used on Fields of Crops with Reported Dacthal Use: California, 2014-2016

	Num.	Number of Fields			Acres Treated		
Crop	Herbicides	2014	2015	2016	2014	2015	2016
Broccoli	1	2,495	2,488	2,540	47,938	45,790	46,758
	2	537	460	478	22,636	17,588	17,493
	3	199	189	171	15,869	14,599	10,574
	4	44	53	41	5,671	7,139	4,518
	5+		11	23		2,246	4,143

[4] A field is defined as a unique combination of the *grower_id* and *site_loc_id* variables in the PUR dataset. The number of herbicides column shows the number of distinct herbicide products used per field. The fields column shows the number of fields that received the corresponding number of distinct herbicide products that year. The acre column shows the number of acres treated with the corresponding number of distinct herbicides. For example, for broccoli in 2014, there were 537 fields treated with two distinct herbicides. The combined treated acreage across all these fields was 22,636 acres. This does not mean that the geographic area of these fields was 22,636 acres, rather than 22,636 acres on these fields were treated with two distinct herbicides at some point in 2014. Applications reported in square feet were converted to acres. A handful of applications were reported with non-standard measures of area treated. In these cases, the acres treated measure was set to zero. Because there were so few applications with non-standard measures of acres treated, this will have a negligible effect on total acres treated. All other crops used standard area measures.

Crop	Num. Herbicides	Number of Fields 2014	2015	2016	Acres Treated 2014	2015	2016
Onion	1	225	222	253	12,956	11,857	16,763
	2	194	225	243	16,302	16,247	19,927
	3	196	166	188	25,446	21,587	27,305
	4	139	155	144	44,318	36,474	41,652
	5+	190	186	167	74,766	71,732	58,435
Cabbage	1	282	341	366	5,762	6,241	6,749
	2	65	56	58	3,478	2,555	3,423
	3	23	19	15	1,366	1,322	1,190
	4	4	5	3	473	426	224
Cauliflower	1	782	992	1,015	15,664	18,554	19,779
	2	108	98	114	4,267	4,506	4,212
	3	33	22	28	1,624	2,183	2,095
	4	16	16	12	429	740	518
	5	3	2	5	33	179	748
Chinese Cabbage	1	135	144	174	1,286	1,422	1,477
	2	31	28	17	501	599	272
	3	10	7	7	547	194	306
	4	1			84		
Bok Choy	1	115	115	147	1,041	945	940
	2	28	22	17	880	265	674
	3	6	7	7	174	240	281
Brussels Sprout	1	39	51	122	663	958	2,269
	2	35	29	54	1,154	657	1,545
	3	1	8	10	19	179	214
	4			8			165
	5		1	4		24	169
Radish	1	23	54	94	885	977	1,123
	2		5	2		181	94
	5			1			39
N-Outdr Flower	1	118	98	93	1,193	965	815
	2	43	56	43	1,023	1,345	1,120
	3	23	20	46	856	825	1,596
	4	11	14	14	620	832	817
	5+	13	18	17	3,210	2,996	2,650
Kale	1	130	184	240	841	1,725	1,636
	2	16	26	15	396	647	324
	3	5	6	9	161	229	636
Rapini	1	17	57	76	444	1,337	1,625
	2	3	6	11	810	1,250	1,162
	3	8	7	4	2,230	1,943	945
	4	1	1		280	210	

Crop	Num. Herbicides	Number of Fields 2014	2015	2016	Acres Treated 2014	2015	2016
Mustard	1	137	24	25	1,792	1,148	710
	2	3	9	7	14	227	294
	3	6	2	8	341	24	289
Leek	1	21	56	28	194	313	172
	2	7	5	33	99	141	292
	3	1		2	30		13
Gai Lon	1	13	15	13	132	132	145
	2	8	4	7	216		88
	3	2	1	1	273	48	56
Kohlrabi	1	4	31	34	52	12	26
	2	7	8	6	42	698	68
	3	3	3	5	31	36	61
N-Outdr Plants in Containers	1	221	222	235	5,941	5,192	5,590
	2	137	134	116	7,963	5,983	3,629
	3	105	74	93	4,363	3,507	4,362
	4	53	64	50	5,164	7,413	5,458
	5+	128	133	104	27,403	25,987	22,305
Onions (Green)	1	13	23	19	258	180	217
	2	4	1	1	101	25	4
	3		1			5	
	6	2			885		
Soil Fumigation/ Preplant	1	1,018	860	448	51,759	56,983	24,415
	2	637	939	644	43,265	74,465	32,055
	3	275	270	235	19,917	24,535	18,326
	4	77	91	69	10,040	13,908	8,601
	5+	35	46	46	4,919	7,905	6,751
Turnip	1	16	17	12	121	127	146
	2	16	6	5	256	104	85
	3	2	3	3	29	28	54
Uncultivated Ag	1	2,071	2,405	2,316	125,513	148,415	126,283
	2	2,167	2,576	2,954	145,065	191,162	210,382
	3	576	810	1,012	59,891	81,252	121,137
	4	179	199	363	19,828	27,383	52,135
	5+	121	122	131	15,596	12,125	22,092
Other	1	7,434	8,028	8,327	121,545	122,265	129,114
	2	1,436	1,635	2,686	68,815	75,050	101,729
	3	320	345	424	24,522	32,885	47,485
	4	84	84	169	10,509	8,873	17,436
	5+	80	71	125	8,051	10,937	17,161
Total		23,766	25,987	27,852	679,597	726,996	708,195

Table 15 shows the number of distinct herbicides growers in Monterey County used on their fields in 2014–2016. Generally, the number of fields and treated acreage declined as the number of distinct herbicide products increased, as was the case for California as a whole. Broccoli is a good example of this pattern. Each year around 1,700 fields used only one herbicide product, accounting for around 20,000 treated acres. Around 300 fields used two distinct herbicide products, accounting for around 6,000 treated acres. The decline in treated acres was proportionally smaller than the decline in number of fields, suggesting that the herbicides were applied to larger fields, the growers applied herbicides at higher rates, or the fields had more frequent applications. This pattern continued for fields receiving three and four distinct herbicide products.

There were three crops where this pattern did not hold for one or more years, and the most frequent number of distinct herbicides used was greater than one. Onions were the most significant example where the most frequent number of distinct herbicides used by number of fields and acres treated was three in 2014 and 2016. In 2015, the most frequent number was four by both measures. This is consistent with the IPM guidelines, which recommend different herbicides at different stages of the onion's life-cycle. This reverse pattern also appeared for Brussels sprout in 2014 and 2015, and leek in 2016, when it was more common for fields to receive two distinct herbicides than a single herbicide. These crops accounted for relatively few treated acres. Brussels sprout accounted for 514 treated acres in 2014, and 122 treated acres in 2015. Leek accounted for 225 treated acres in 2016.

Table 15. Number of Distinct Herbicide Products Used on Fields of Crops with Reported Dacthal Use: Monterey County, 2014-2016

Crop	2014			2015			2016		
	Num. Herbicides	Fields	Acres Treated	Num. Herbicides	Fields	Acres Treated	Num. Herbicides	Fields	Acres Treated
Bok Choy	1	38	109	1	34	79	1	63	131
	2	2	9	2	9	27			
Broccoli	1	1,699	20,551	1	1,746	19,697	1	1,860	21,514
	2	341	7,170	2	281	5,529	2	319	6,255
	3	56	1,780	3	66	1,932	3	65	1,481
	4	6	92	4	9	155	4	3	59
Brussels Sprout	1	3	65	1	9	91	1	78	1,000
	2	15	449	2	12	131	2	9	107
Cabbage	1	105	1,114	1	135	1,135	1	195	1,933
	2	1	20				2	9	59
Cauliflower	1	479	5,796	1	585	6,409	1	647	7,314
	2	30	507	2	16	396	2	38	497
	3	2	34				3	5	16
Chinese Cabbage	1	35	199	1	39	178	1	79	289
	2	1	6	2	6	38	2	1	4
Kale	1	84	461	1	130	1,001	1	189	1,221
	2	2	3						
Kohlrabi	1	1	0	1	30	11	1	33	21
Leek	1	12	90	1	31	121	1	15	77
							2	24	148
							3	1	7
Lettuce, Head	1	1,456	19,305	1	1,561	20,936			
	2	310	5,625	2	260	4,780			
		10	279	3	18	434			
	3								
Lettuce, Leaf							1	2483	31,017
							2	906	15,442
							3	32	1,223
Mustard (Mizuna)	1	47	172						
Mustard Greens							1	70	330
Onion	1	28	441	1	35	692	1	34	633
	2	18	663	2	31	1,151	2	34	1,263
	3	52	2,596	3	32	1,676	3	52	2,707
	4	19	1,337	4	41	2,402	4	20	1,480
	5	9	921	5	6	522			

Crop	2014 Num. Herbicides	2014 Fields	2014 Acres Treated	2015 Num. Herbicides	2015 Fields	2015 Acres Treated	2016 Num. Herbicides	2016 Fields	2016 Acres Treated
	6	1	198	6	1	52			
Onions (Green)	1	4	21	1	15	87	1	10	18
Radish				1	29	49	1	61	126
Soil Fumigation/	1	240	3,376						
Preplant	2	21	445						

Source: Authors' calculations derived from the CDPR Pesticide Use Report data.

Table 16 shows the number of distinct herbicides growers in Santa Barbara County used on their fields in 2014–2016. Like Monterey County, the general trend was for the number of fields and acres treated to decline with the number of distinct herbicides used. The most striking exceptions to this trend were the fields used for nurseries, both outdoor container/field nurseries, and outdoor grown cut flowers and greens nurseries. In both cases there were one or two fields accounting for the largest number of acres treated, and these fields had four or five distinct herbicides applied (4–5). This suggests there were a small number of large nurseries growing a variety of different plants, which explains both the high number of distinct herbicides and the high number of acres treated.

Brussels sprout, kale, and kohlrabi used two distinct herbicides more frequently than a single herbicide. Dacthal was only applied to onions in Santa Barbara in 2015. Although the acres treated were high (around 4,500) the number of fields was small. These fields used a larger variety of herbicides than onion growers in Monterey and San Luis Obispo counties. Six was the most common number of distinct herbicides, applied to 3,009 acres, followed by four distinct herbicides, applied to 1,540 acres.

Table 16. Number of Distinct Herbicide Products Used on Fields of Crops with Reported Dacthal Use: Santa Barbara County, 2014-2016

Crop	2014 Num. Herbicides	2014 Freq.	2014 Acres Treated	2015 Num. Herbicides	2015 Freq.	2015 Acres Treated	2016 Num. Herbicides	2016 Freq.	2016 Acres Treated
Bok Choy	1	6	87	1	10	222	1	17	228
				2	2	24	2	3	91
Broccoli	1	255	14,238	1	224	14,183	1	262	13,581
	2	53	8,123	2	56	4,980	2	39	2,879
	3	34	4,190	3	24	3,385	3	18	1,770
	4	9	1,500	4	10	2,275	4	9	1,523
				5	2	516	5	5	1,215
							9	1	493
Brussels Sprouts	1	4	63	1	7	74	1	2	27
	2	9	335	2	7	303	2	16	752
				3	1	35	3	2	41

Crop	2014 Num. Herbicides	2014 Freq.	2014 Acres Treated	2015 Num. Herbicides	2015 Freq.	2015 Acres Treated	2016 Num. Herbicides	2016 Freq.	2016 Acres Treated
				5	1	24			
Cauliflower	1	132	6,496	1	153	8,325	1	140	8,168
	2	34	1,614	2	30	1,707	2	34	1,225
	3	11	929	3	11	929	3	13	1,105
	4	5	302	4	7	420	4	5	416
	5	2	22	5	1	179	5	5	748
Chinese Cabbage	1	10	214	1	22	502	1	18	367
	2	1	8						
Collards	2	1	12	2	1	5			
Kale	2	5	50	1	1	7	1	2	10
				2	8	109	2	5	133
Kohlrabi	1	2	50						
				2	2	658	2	3	57
Leek				1	1	7	1	1	21
Mustard Greens	2	4	18	2	1	15			
Nursery - Outdoor Container/Field	1	8	84	1	7	219	1	7	50
	2	5	311	2	4	98	2	5	217
	3	1	142	3	4	532	3	4	295
	4	2	1,758	4	2	1,976	4	1	297
	5	2	7,687						
							9	1	1,504
Nursery - Outdoor Grown Cut Flowers or Greens	1	34	372	1	34	467	1	28	355
	2	13	613	2	21	824	2	16	616
	3	2	14	3	1	200	3	2	172
	4	3	377	4	2	209	4	1	377
				5	2	956	5	1	852
	6	1	1,189						
Onion				2	1	1			
				4	1	1,540			
				6	3	3,009			
Radish	1	1	1	1	1	1			
Tomato							2	1	2
Turnip							1	2	31

Source: Authors' calculations derived from the CDPR Pesticide Use Report data.

Table 17 shows the number of distinct herbicides that growers in San Luis Obispo County used on their fields in 2014–2016. Like Monterey County, the general trend was for the number of fields and acres treated to decline with the number of distinct herbicides used. Overall, there were also fewer fields and acres treated. Onion was the notable exception to this trend, with four distinct herbicides being most common by fields and acres treated in 2014. Dacthal was not used on fields growing onions in 2015 and 2016. Brussels sprout in 2016 was another counterexample, with two distinct herbicides being most common by number of fields and treated acreage.

While the number of fields declined with the number of distinct herbicide products for broccoli, the same was not true for acres treated. In each year, more acres were treated with three distinct herbicides than were treated with two, suggesting that there were either large fields using three herbicides, that the growers operating these fields used higher application rates, or had more frequent applications.

Table 17. Number of Distinct Herbicide Products Used on Fields of Crops with Reported Dacthal Use: San Luis Obispo County, 2014-2016

	2014			2015			2016		
Crop	**Num. Herbicides**	**Fields**	**Acres Treated**	**Num. Herbicides**	**Fields**	**Acres Treated**	**Num. Herbicides**	**Fields**	**Acres Treated**
Bok Choy	1	45	167	1	46	213	1	43	185
	2	3	17	2	1	7	2	2	6
Broccoli	1	383	6,385	1	409	6,559	1	268	4,859
	2	61	970	2	26	547	2	9	354
	3	36	1,340	3	14	1,013	3	7	600
	4	5	144	4	1	89	4	4	274
				5	1	120	5	2	162
Brussels Sprout	1	17	160	1	15	96	1	13	87
	2	6	74	2	6	55	2	23	375
	3	1	19	3	6	108	3	7	125
							4	8	165
							5	4	169
Cabbage	1	51	378	1	74	613	1	50	442
	2	14	73	2	6	52	2	1	13
	3	3	16	3	2	24			
Cauliflower	1	121	1,458	1	205	2,360			
	2	14	155	2	18	414			
	3	16	232	3	2	45			
	4	11	127	4	7	109			
	5	1	11	5	1	0			
Chinese Cabbage	1	72	639	1	69	540	1	58	582
	2	16	243	2	9	159	2	8	79
	3	2	45						
Kale	1	15	75	1	15	154	1	7	25

Crop	2014 Num. Herbicides	2014 Fields	2014 Acres Treated	2015 Num. Herbicides	2015 Fields	2015 Acres Treated	2016 Num. Herbicides	2016 Fields	2016 Acres Treated
				2	1	4	2	1	2
Kohlrabi				2	1	0			
Leek	1	2	15	1	8	30	1	4	17
				2	1	2			
Mustard Greens	2	1	0						
Nursery - Outdoor Grown Cut Flowers or Greens	1	3	32						
	4	1	7						
	5	1	15						
Onion	1	3	3						
	2	3	24						
	3	4	132						
	4	2	36						
	6	2	57						
Onion (Green)				1	2	1	1	1	1
Radish	1	1	1	1	1	1	1	1	0
Tomato							2	1	3

Source: Authors' calculations derived from the CDPR Pesticide Use Report data.

IPM Overview

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. On a pound per pound basis dacthal is used at very high rates of up to 10.5 lbs. per acre (AMVAC Chemical Corporation 2015). Primary weeds controlled by dacthal are annual grass weeds and some small-seeded annual broadleaf weeds like lambsquarters and pigweed. Dacthal provides partial control of many other weeds such as little mallow, hairy nightshade, and burning nettle (UCIPM 2007). In onion, dacthal is used to control or suppress weeds until the onions are large enough to withstand oxyfluorfen and bromoxynil applications over the top. Onion is very susceptible to weed competition at all growth stages as it is slow growing and does not develop a crop canopy to suppress weeds like corn or cotton (Hembree et. al. 2014; UCIPM 2010). In the brassica crops, the role of dacthal is to provide partial weed control during crop establishment that is supplemented by cultivation and hand weeding. In all of the crops that use dacthal, cultural and physical weed control tools are necessary to provide commercially acceptable weed control.

Cultural and physical weed control before planting

A stale seedbed method of reducing weed densities is a useful weed control technique in vegetable crops, including allium and brassica crops. The concept depends on controlling the final flush of weeds before crop emergence, followed by minimal soil disturbance to reduce subsequent weed flushes. This method involves first preparing a seedbed and irrigating it to germinate weed seeds, then using shallow tillage, propane flaming, or herbicide to kill germinated weeds. The crop is then planted, or the process repeated to provide even better weed control. In the case of direct-seeded crops like onion, an additional step can be taken to treat the field with an herbicide or with a propane flamer to kill all emerged weeds just before the crop emerges (UCIPM 2008).

Soil solarization is a nonchemical, soil pasteurization process that will control most weeds prior to vegetable planting. To solarize, clear plastic is placed on top of the moist, clean seedbed for four to six weeks during the hottest part of the year. Because soil solarization requires a summer fallow season for treatment, it fits in best with a fall-planted crop. Solarization works well in the low desert and central valley of California. However, in coastal areas, foggy conditions during summer can greatly reduce the efficacy of solarization, limiting its usefulness (Elmore et al. 1997).

Proper bed preparation is important for successful weed cultivation after the crop is planted. Poorly leveled land will cause water to collect in low areas of the field, favoring growth of water-loving weeds. Effective cultivation of bed tops requires precise row spacing and careful alignment of cultivating tools. GPS-assisted, auto-guidance systems create precision aligned beds that facilitate accurate weed cultivation in closely planted crops.

Cultural and physical control after planting

Control of weeds after planting is most critical during the seedling stage, when competition from weeds is the most detrimental to crop development. Once established (4–5 inches tall), most cole crops, with the exception of cabbage, can shade out weeds. Onion, however, continues to be susceptible to weed competition for most of the cropping season. One method of cultural control is to scout for flowering wind-dispersed weeds (such as annual sowthistle), and destroy them before they produce seed to prevent dispersal and establishment in fields.

Effective mechanical cultivation of bed tops requires precise row spacing and careful alignment of cultivating tools. When plants have two to three leaves, sweeps or knives can be set as close as two inches on each side of the seed rows as long as they cultivate shallowly; closer cultivation will cut feeder roots. When crop seedlings are tall enough that they will not be buried, usually when they have three to four leaves, tools are arranged so they move a 1-inch layer of soil toward and into the seed row. This mulch of dry soil prevents many weed seeds from germinating.

Lati et al. (2016) examined weed density and hand weeding times with and without herbicides. In lettuce (with propyzamide), plots without herbicide had approximately 20 percent higher weed densities and hand-weeding times increased by a factor of 3.6. In broccoli (with dacthal), plots without herbicide had statistically indistinguishable weed densities but hand-weeding times again increased, though by a slightly lower factor of 3.2. Across the two crops, on average, hand-weeding times increased by a factor of 3.4 without herbicides. Lati et al. (2016) also examined the benefits of an intelligent cultivator (specifically the *Robovator,* F. Poulsen Engineering ApS, Hvalsø, Denmark) in weed control for broccoli and lettuce. Intelligent cultivators are an emerging technology—combining robotics, machine vision and machine learning—with the potential to greatly improve weed control in vegetables, especially minor crops. When weed density was moderate (> 100 weeds m^{-2}) or higher, the intelligent cultivator reduced weeds by 18 to 41 percent and hand-weeding time by 20 to 45 percent without a reduction in yield or crop stand.

Hand weeding has been an essential part of the weed control program in all of the crops that use dacthal for a very long time, and this practice continues to the present. However, given the high cost and increasing shortages of labor, hand weeding should not be relied upon as the solution should dacthal no longer be available (Taylor et al. 2012). If dacthal is no longer available, the weeding costs for all crops that use this product will increase. We do not have the current cost of hand weeding in organic brassica crops that would allow us to estimate the cost of the loss of dacthal in crops like bok choy. Therefore, we used hand weeding costs in lettuce as a proxy. In a 2009 the cost of two passes by a hand thinning/weeding crew resulted in a cost of $217 per acre in conventional lettuce and $381 per acre in organic lettuce (Smith et al. 2009; Tourte et al. 2009). In other words, weed related labor costs in organic lettuce were 44% higher where no herbicide was used compared to $217 in conventional lettuce where an herbicide was used.

If dacthal were no longer available, it is likely that need for hand weeding would increase in crops like bok choy and radish. Given the increasing cost and scarcity of labor, the production costs for crops like onion, radish and bok choy will likely increase. The result of this could force more production from California to areas like Mexico where labor costs are lower.

Alternative Herbicides

The availability and efficacy of alternative herbicides varies significantly by crop. Oxyfluorfen (e.g., GoalTender) is safe to broccoli and cauliflower, and very effective on a number of key weeds. The main concern for the loss of dacthal would be for the small acreage crops more dependent on dacthal: bok choy, Brussels sprout, radish, kale, rapini, mustards, gai lon and kohlrabi (Table 18). These crops do not have a good alternative to dacthal currently registered. Onion has no alternative to dacthal in the at-planting time slot (Table 19).

Because of the cropping scheme on the high-value lands of the coastal valleys, often two, three or even four rotational crops are planted on the same acre in a given year. Fields in the Salinas Valley or Santa Maria Valley may see broccoli, celery, lettuce, and spinach all grown in the same year. Herbicides used in one crop absolutely cannot injure rotational crops, i.e., must have a short period of soil residual activity. Any herbicide that is to replace dacthal must not carryover to injure rotational crops like celery, lettuce, and spinach. Because dacthal can be used on so many crops and has short life in the soil, carryover injury to rotational crops is not a major issue with this herbicide.

Table 18. Herbicides Available for Brassica Leafy Vegetables in California by Use Pattern: Preemergence, Burndown and Postemergence Grass*

Crop /group	Preemergence	Burndown	Postemergence grass
Bok choy 5B	Bensulide Clomazone Clopyralid Dacthal Trifluralin	Glyphosate Paraquat	Clethodim
Brussels sprout 5A	Bensulide Clomazone Clopyralid Dacthal Napropamide Pendimethalin Trifluralin	Carfentrazone Glyphosate Pyraflufen	Clethodim
Kale 5B	Bensulide Clomazone Clopyralid Dacthal Napropamide Pendimethalin Trifluralin	Glyphosate	Clethodim Sethoxydim
Rapini (Broccoli raab) 5B	Bensulide Dacthal Clopyralid	Glyphosate	--
Mustards 5B	Bensulide Clopyralid Dacthal Napropamide Pendimethalin Trifluralin	Glyphosate Carfentrazone	Clethodim Sethoxydim
Gai lon (Chinese broccoli	Bensulide Dacthal	--	--
Kohlrabi 5A	Bensulide Clomazone Clopyralid Dacthal Pendimethalin Trifluralin	Glyphosate	Clethodim

*Crop groups listed are US EPA crop groups 5A brassica vegetables, and 5B leafy brassica greens (US EPA crop groups). See Agrian http://www.agrian.com/labelcenter/results.cfm for product label.

Table 19. Onion, Garlic and Leek Herbicides by Growth Stage*

Crop	Preplant	At planting	Post planting	Crop established
Onion	Glyphosate Metam sodium Paraquat	Dacthal	Ethofumesate	Bensulide Bromoxynil Clethodim Dimethenamid-P Ethofumesate Fluazifop P Pendimethalin Oxyfluorfen Sethoxydim Trifluralin – layby
Leek	Glyphosate	Dacthal		Clethodim Dimethenamid-P Pendimethalin

*See Agrian http://www.agrian.com/labelcenter/results.cfm for product label.

Literature review

Relatively little published research is available regarding the efficacy of dacthal as an herbicide for brassica or allium crops. Much of it was conducted in Arizona, rather than on California's Central Coast. One or both of two key herbicide attributes are considered in these studies: the extent of weed control, and crop yields. Of note, yield can be affected by the herbicide damaging the plants as well as by competition between the crop and weeds for water and nutrients. In light of the lack of published research, we also used information collected from unpublished reports, product labels, and knowledgeable weed management specialists.

Broccoli

Overall, studies found that dacthal provided acceptable or good weed control (Umeda and Gill 1995; Umeda 2000; Lati et al. 2016). Fischer, Hoyle and May (1971) found that dacthal paired with propham provided the best control of the herbicide programs considered.[5] Lati et al. (2016) found that it left crop yield unaffected.

Onion

Studies of dacthal applied to onion were all conducted in Arizona. Unlike for broccoli, dacthal negatively affected onion. Umeda and Gal (2007) found it reduced onion height by roughly 40%. In anticipation of the loss of Dacthal 7 for onion, Umeda and MacNeil (1997) compared dacthal to pendimethalin (Prowl), bensulide (Prefar), and pendimethalin combined with other herbicides. They found that yields were statistically the same for all treatments. Pendimethalin provided slightly better control than dacthal, with the exception of yellow sweetclover, which dacthal did not control. Also motivated by the anticipated loss of dacthal, Umeda et al. (1999) compared

[5] Propham has no currently registered products in the U.S.

dacthal to potential alternatives and found that dacthal provided equivalent or superior weed control to pendimethalin, bensulide, or a combination of pendimethalin and bensulide, with the difference dependent on the weed. In contrast to the 1997 study, dacthal provided substantially better control of yellow sweetclover.

Bok Choy

Fennimore *et al*. (unpublished) conducted a small study in Salinas comparing weed control methods on bok choy. Plants were direct seeded, then thinned and weeded with a hoe. Three control methods were considered: dacthal at 10 pints per acre, Prefar 4-E (bensulide) at 6 pints per acre, and non-treated. The dacthal treatment provided 95 percent weed control, and required 16.5 additional hours of hand weeding. The Prefar 4-E treatment provided 71 percent weed control, and required an additional 22.9 hours of hand weeding. The non-treated crop required 30.2 hours of additional hand weeding time. Comparing the hand weeding time between the dacthal and bensulide treatments, hand weeding time increased by 39 percent.

Efficacy of potential partial alternatives

The herbicides registered on the brassica vegetables fall into three categories: preemergence, burndown, and postemergence grass herbicides. Dacthal is a soil applied preemergence herbicide applied at planting to control many broadleaf and grass weeds. However, it is weak on weeds in the mustard family such as shepherd's-purse (AMVAC Chemical Co. 2015).
The burndown herbicides like glyphosate and paraquat are applied before planting or before crop emergence, i.e., burndown weeds, and cannot be applied after crop emergence. Therefore, the burndown herbicides are of limited utility because they cannot be used during the cropping season. The postemergence grass herbicides, like clethodim, only control grass weeds, however, most of the weeds in Coastal California are broadleaf weeds and clethodim is not often used on these crops, so it too is of limited utility (Valent USA 2015). In addition, the safety to rotational crops is an important consideration while looking at alternatives.

Bensulide (e.g., Prefar 4E) is a preemergence herbicide registered on several of the brassica leafy vegetables (Table 3). This herbicide is closely related to the organophosphate insecticides and is a unique product that controls a limited number of weeds. Bensulide (Prefar 4-E) product label claims to control only seven grass weeds and five broadleaf weeds (Gowan Co. n.d.). Registered crops on the Prefar label include brassica leafy vegetables, bulb onion and shallots. Overall, bensulide controls a limited weed spectrum and should not be considered a direct replacement for dacthal (Gowan Co. n.d.).

Bromoxynil (e.g., Brox 2E) is labelled on bulb onion and garlic but for use only after crop establishment (Table 3). Bromoxynil is an important herbicide for allium crops but the use pattern is much later in the growth cycle than dacthal (Albaugh Chemical Co. n.d.). Where dacthal is applied at planting in onion, the weeds are stunted or delayed in growth while the onion emerges and begins to develop. Then later, bromoxynil can be applied after the onion has reached size where it can tolerate this herbicide but before the weeds have grown too large to control. Therefore, dacthal is the foundation for weed control in direct seeded onion (Hembree et al. 2014). Bromoxynil alone would not provide the same control.

Clethodim (e.g., Select Max) is labelled on broccoli, cabbage, cauliflower (and other head and stem brassica vegetables), mustard greens (and other leafy brassica greens), onions (dry bulb and green), radish, shallot (dry bulb), and turnip greens. Crop safety with clethodim is excellent on all of these vegetables. However, clethodim only controls grass weeds and does not control any broadleaf weeds (Valent USA 2-15), meaning that it cannot fully replace dacthal.

Clomazone and clopyralid are labelled for use on many of these crops but both of these herbicides have a long-lived soil residues and potential carryover to rotational crops. Clomazone is registered for brassica head and stem vegetables but has a plantback restriction of 12 months that would not permit planting of common rotational crops like celery, lettuce, onion and spinach (Willowood USA 2016). Clopyralid (e.g., Stinger) is registered on the brassica vegetables crop group 5 but is not registered on onion. Clopyralid has a statement on the label cautioning that injury to rotational crops can occur as long as 4 years after application (Dow AgroSciences 2014d). High probability of carryover injury to sensitive rotational crops disqualifies these two herbicides as replacements for dacthal.

Dimethenamid-P (e.g., Outlook) is labelled for onion, leek and shallots (BASF Co. 2017). This product provides yellow nutsedge and broadleaf weed control. Dimethenamid-P is applied at or after the second true leaf stage of onions but before nutsedge emerges. Because Dimethenamid-P can only be applied after the two leaf stage of onion, it cannot replace the role of dacthal during onion emergence.

Ethofumesate (e.g., Nortron) is registered for use on onion preemergence. This product has a very narrow weed spectrum and tends to be injurious to onion (Rob Wilson, UCANR Intermountain REC, personal communication). Ethofumesate was found to provide poor control of the weed nettleleaf goosefoot and may reduce onion yields (Richard Smith, UCCE Monterey, unpublished results). Additionally, at the rates used in onion of 16 to 32 oz product per acre, the plantback interval for most vegetable rotational crops would be 12 months (Bayer CropScience 2013). Thus, ethofumesate is not a viable replacement for dacthal on onion.

Oxyfluorfen**.** The oxyfluorfen product GoalTender can be applied for postemergence control in direct-seeded or transplanted broccoli and cauliflower (Dow AgroSciences 2006). Oxyfluorfen provides good control of a broad spectrum of broadleaf annual weeds and is safe on transplanted broccoli or cauliflower. It is less effective in controlling large lambsquarters and grass weeds and does not control yellow nutsedge. In onion, oxyfluorfen can be applied at the 1 leaf state as per a Special Local Needs label (Dow AgroSciences 2010). Oxyfluorfen is registered on broccoli, cabbage, cauliflower, onions, and onions grown for seed (Dow AgroSciences 2014a). Oxyfluorfen is a potential replacement for dacthal in broccoli and cauliflower. No oxyfluorfen products, however, are registered for use in Brussels sprout, cabbage, bok choy, radish, or a number of small acreage brassica crops. In allium crops, oxyfluorfen is registered on bulb onion but not on green onion or leek. The critical niche in the onion weed control program provided by dacthal that is not filled by oxyfluorfen is the weed control during onion emergence and establishment.

Napropamide (e.g., Devrinol) provides excellent control of all annual grasses, including volunteer cereals and a large number of broadleaf weeds. In California, napropamide is registered on broccoli, Brussels sprout and cauliflower (United Phosphorus Inc. 2016). It has long residual properties and a narrow range of crop tolerances. The rotational crop restrictions on the label are 60 days for leafy vegetables and 12 months for all other crops not on the label (United Phosphorus Inc. 2016). As a replacement for dacthal, napropamide would be most suited for Brussels sprout, though the 12 month rotational crop restrictions could be a problem for crops like celery and onion.

Pendimethalin (e.g., Prowl H_2O) provides excellent control of grass weeds and some small seeded broadleaf weeds like chickweed, pigweed, and purslane. Pendimethalin is registered on broccoli, Brussels sprout, cabbage, cauliflower, onion and shallot. Pendimethalin may be the closest treatment to filling the role of dacthal in early season onion. Pendimethalin can be applied to partially emerged onion (BASF Corporation 2006, 2015). Carryover to rotational crops is a concern with plantback intervals of 12 to 20 months for most vegetables, with the exception of fruiting vegetables like peppers and tomato, for which there are no plantback restrictions (BASF Corporation 2016). Pendimethalin may be a partial replacement for dacthal but the limited broadleaf weed spectrum and rotational crop restrictions constrains its utility.

Trifluralin (e.g., Treflan HFP) is registered on a number of the crops that use dacthal including broccoli, Brussels sprout, cabbage, cauliflower, celery, collard greens, mustard greens, onions, radish, and turnip greens (Dow AgroSciences 2014e). Trifluralin must be mechanically incorporated 2 to 3 inches deep; once incorporated, it remains stable. Trifluralin mostly controls grass weeds and small-seeded broadleaves like purslane and pigweeds (UCIPM 2007). Trifluralin controls a somewhat limited spectrum of weeds and has a long residue period. Residues harmful to acutely sensitive crops like spinach, sugarbeets, milo, and corn, may persist up to 12 months. Trifluralin is labelled on a large number of crops that use dacthal as well as a large number of crops that are in rotation with crops dependent on dacthal such as carrot and celery. However, trifluralin is only a partial replacement for dacthal given its limited broadleaf weed spectrum control.

Sulfentrazone (e.g., Zeus) is registered on seeded and transplanted cabbage in California (FMC Corporation 2010). Recently, food use tolerances were granted on a number of brassica crops: Brassica leafy greens subgroup 4-16B, head and stem brassica vegetable group 5-16, stalk and stem vegetable subgroup 22A (Federal Register 4/13/2018). However, the only crop with a California registration is cabbage. Data from Salinas, CA indicate excellent crop safety of sulfentrazone to broccoli, collard and kale (Haar et al. 2002; Fennimore and Rachuy 2006). However, the plantback issues with this herbicide may greatly limit its utility as spinach is very sensitive to carryover from sulfentrazone (Fennimore unpublished data).

UC IPM Program Spectrum of Control of Weeds by Herbicide: Cole Crops and Onion

Table 20 through Table 24 report the spectrum of control for dacthal and related herbicides for annual and perennial weeds in both onions and garlic from the UC Integrated Pest Management (2007, 2008) guidelines. As reflected in the tables, dacthal is particularly effective at controlling most grasses and some broadleaf weeds. Most importantly, the tables clearly illustrate that none of the other herbicides provide the same spectrum of control as dacthal in cole crops or onions.

Table 20. Spectrum of Control on Annual Weeds for Cole Crops.

Annual Weeds	Dacthal	Bensulide	Trifluralin	Napropamide	Oxyfluorfen	Clethodim	Sethoxydim	EPTC	Glyphosate	Metam sodium*	Paraquat*	Pelargonic acid	Carfentrazone
Barley, Foxtail	**C**	C	C	C	N	C	C	C	C	C	C	—	N
Barnyardgrass	**C**	C	C	C	P	C	C	C	C	C	P	C	N
Bluegrass, Annual	**C**	C	C	C	P	C	N	C	C	C	P	C	N
Canarygrass, Littleseed	**C**	C	C	C	P	C	C	C	C	C	P	—	N
Chickweed, Common	**C**	P	C	C	N	N	N	C	C	C	C	C	P
Goosefoot, Nettleleaf	**C**	P	C	C	C	N	N	C	C	C	C	—	—
Groundcherries	**C**	N	N	N	C	N	N	C	C	C	C	—	C
Groundsel, Common	**N**	N	N	P	C	N	N	C	C	C	C	C	—
Knotweed, Prostrate	**P**	C	C	C	P	N	N	P	P	C	P	C	—
Lambsquarters, Common	**C**	P	C	C	C	N	N	C	C	P	P	P	—
Lettuce, Prickly	**N**	N	N	C	C	N	N	C	C	C	P	—	—
Little Mallow (Cheeseweed)	**P**	N	N	P	C	N	N	N	P	P	P	C	C
Mustards	**P**	N	N	P	C	N	N	N	C	C	C	C	P
Nettle, Burning	**P**	N	P	P	C	N	N	C	N	C	P	—	C
Nightshade, Black	**P**	N	N	N	C	N	N	P	C	C	C	—	N
Nightshade, Hairy	**P**	N	N	N	C	N	N	C	C	C	C	—	N
Oat, Wild	**P**	N	P	C	P	C	C	C	C	C	P	—	N
Pigweeds	**C**	C	C	C	C	N	N	C	C	C	C	P	—
Pineapple-Weed	**N**	N	N	P	P	N	N	C	C	—	P	—	N
Polypogon, Rabbitfoot	**—**	C	C	C	N	C	C	C	C	—	C	—	N
Purslane, Common	**C**	C	C	C	C	N	N	C	C	C	P	C	N
Radish, Wild	**N**	N	N	P	C	N	N	N	C	C	C	—	P
Rocket, London	**P**	N	N	C	C	N	N	C	C	C	P	C	C
Shepherd's-Purse	**N**	N	N	P	P	N	N	P	C	C	P	C	P
Sowthistles	**P**	N	N	C	C	N	N	C	C	C	P	—	N
Volunteer Grains	**P**	N	C	C	N	C	C	C	C	C	P	—	N

Source: UC IPM Pest Management Guidelines: Cole Crops (UC ANR Pub. No. 3442).

Notes: C = control; P = partial control; N = no control; — = no information; * - permit required from county agricultural commissioner for purchase or use; color shading: green – improvement of control compared to dacthal, yellow partial loss of control compared to dacthal, complete loss of control compared to dacthal.

Table 21. Spectrum of Control on Perennial Weeds for Cole Crops.

Perennial Weeds	Dacthal	Bensulide	Trifluralin	Napropamide	Oxyfluorfen	Clethodim	Sethoxydim	EPTC	Glyphosate	Metam sodium*	Paraquat*	Pelargonic acid	Carfentrazone
Bindweed, Field (seedlings)	**N**	N	P	N	N	N	N	N	C	P	P	—	C
Nutsedge, Purple	**N**	N	N	N	N	N	N	P	P	P	N	N	N
Nutsedge, Yellow	**N**	N	N	N	N	N	N	P	P	C	N	N	N

Source: UC IPM Pest Management Guidelines: Cole Crops (UC ANR Pub. No. 3442).

Notes: C = control; P = partial control; N = no control; **—** = no information; * - permit required from county agricultural commissioner for purchase or use; color shading: green – improvement of control compared to dacthal, yellow partial loss of control compared to dacthal, complete loss of control compared to dacthal.

Table 22. Spectrum of Control on Annual Weeds for Onion and Garlic (1 of 2).

Annual Weeds	**Dacthal**	**Bensulide**	**Ethofumesate**	**Glyphosate**	**Paraquat***	**Metam Sodium***	**Bromoxynil**	**Oxyfluorfen**	**Dimethenamid**	**Sethoxydim**	**Fluazifop-P-Butyl**	**Clethodim**	**Pendimethalin**
Barley, Hare	**C**	P	C	C	P	C	N	P	C	C	C	—	P
Barnyardgrass	**C**	C	P	C	P	C	N	P	C	C	C	C	C
Bluegrass, Annual	**C**	C	C	C	P	C	N	P	C	N	N	C	C
Burclover, California	**—**	N	—	P	P	N	N	P	—	N	N	N	N
Canarygrass	**C**	C	C	C	P	C	N	P	—	C	C	C	C
Cereals	**C**	N	C	C	P	C	N	P	—	C	C	—	P
Chickweed, Common	**C**	P	C	C	C	C	N	N	C	N	N	N	C
Crabgrasses	**C**	C	P	C	C	C	N	N	C	C	C	—	C
Cudweeds	**N**	N	C	C	N	C	C	N	—	N	N	N	N
Dodders	**C**	N	N	C	C	C	N	N	—	N	N	N	N
Fiddlenecks	**C**	N	C	C	P	C	C	C	—	N	N	N	C
Filarees	**P**	N	P	P	P	C	P	C	—	N	N	N	N
Fleabane, Hairy	**N**	N	P	C	C	C	C	P	—	N	N	N	N
Foxtails	**C**	C	C	C	C	C	N	N	C	C	C	C	C
Goosefoot	**C**	P	C	C	C	C	C	C	—	N	N	N	C
Groundcherries	**C**	N	C	C	C	C	C	C	C	N	N	N	P
Groundsel	**N**	N	P	C	C	C	C	C	—	N	N	N	N
Henbit	**P**	N	P	C	C	C	C	C	—	N	N	N	C
Horseweed	**N**	N	P	C	P	C	C	P	—	N	N	N	N
Knotweed, Common	**P**	C	C	C	P	C	P	P	—	N	N	N	C
Lambsquarters, Common	**C**	P	C	C	P	C	C	C	C	N	N	N	C

Source: UC IPM Pest Management Guidelines: Onion and Garlic (UC ANR Pub. No. 3453).

Notes: C = control; P = partial control; N = no control; — = no information; * - permit required from county agricultural commissioner for purchase or use; color shading: green – improvement of control compared to dacthal, yellow partial loss of control compared to dacthal, complete loss of control compared to dacthal.

Table 23. Spectrum of Control on Annual Weeds for Onion and Garlic (2 of 2).

Annual Weeds	Dacthal	Bensulide	Ethofumesate	Glyphosate	Paraquat*	Metam Sodium*	Bromoxynil	Oxyfluorfen	Dimethenamid	Sethoxydim	Fluazifop-P-Butyl	Clethodim	Pendimethalin
Lettuce, Prickly	**N**	N	C	C	P	C	C	C	—	N	N	N	N
Lovegrasses	**C**	C	—	C	P	C	N	C	—	C	C	—	C
Mallow, Little (Cheeseweed)	**N**	N	P	P	N	N	P	C	—	N	N	N	P
Morningglories	**N**	N	C	C	P	P	C	C	—	N	N	N	N
Mustards	**P**	N	N	C	C	C	C	C	—	N	N	N	N
Nettles	**P**	N	P	N	P	C	C	C	C	N	N	N	N
Nightshade, Black	**P**	N	P	C	C	P	C	C	P	N	N	N	N
Nightshade, Hairy	**P**	N	C	C	C	C	C	C	P	N	N	N	N
Oat, Wild	**P**	N	C	C	P	C	N	P	—	C	C	C	P
Panicum, Fall	**C**	C	—	C	P	C	N	N	—	C	C	—	C
Pigweeds	**C**	C	P	C	C	C	C	C	C	N	N	N	C
Puncturevine	**P**	N	C	C	C	C	C	C	—	N	N	N	P
Purslane, Common	**C**	C	C	C	C	C	N	C	C	N	N	N	C
Radish, Wild	**N**	N	N	C	C	C	C	P	—	N	N	N	N
Rocket, London	**P**	N	N	C	C	C	C	C	—	N	N	N	C
Ryegrasses	**C**	P	N	C	P	C	N	N	C	C	C	—	C
Shepherd's-Purse	**N**	N	N	C	P	C	C	C	—	N	N	N	N
Sowthistles	**P**	N	C	C	P	C	C	C	—	N	N	N	N
Sunflowers	**P**	N	N	C	P	C	C	C	—	N	N	N	N
Sweetclovers	**N**	N	—	P	P	N	N	P	—	N	N	N	N
Thistle, Russian	**N**	N	P	C	C	C	C	P	—	N	N	N	P

Source: UC IPM Pest Management Guidelines: Cole Crops (UC ANR Pub. No. 3442).

Notes: C = control; P = partial control; N = no control; — = no information; * - permit required from county agricultural commissioner for purchase or use; color shading: green – improvement of control compared to dacthal, yellow partial loss of control compared to dacthal, complete loss of control compared to dacthal.

Table 24. Spectrum of Control on Perennial Weeds for Onion and Garlic.

Perennial Weeds	**Dacthal**	**Bensulide**	**Ethofumesate**	**Glyphosate**	**Paraquat***	**Metam Sodium***	**Bromoxynil**	**Oxyfluorfen**	**Dimethenamid**	**Sethoxydim**	**Fluazifop-P-Butyl**	**Clethodim**	**Pendimethalin**
Bermudagrass (plant)	**N**	N	N	C	N	P	N	N	—	P	P	P	N
Bermudagrass (seedling)	**C**	N	—	C	P	C	N	N	—	C	C	C	C
Bindweed, field (plant)	**N**	N	N	P	N		N	N	N	N	N	N	N
Bindweed (seedling)	**N**	N	N	C	P	P	P	N	—	N	N	N	P
Dock, curly (plant)	**N**	N	N	—	N	C	N	N	—	N	N	N	N
Dock, curly (seedling)	**C**			C	C	C	C	C	—	N	N	N	C
Johnsongrass (plant)	**N**	N	N	C	N	C	N	N	—	C			N
Johnsongrass (seedling)	**C**	C	C	C	C	C	N	N	C	C	C	C	C
Nutsedge, purple	**N**	N	P	P	N	N	N	N	—	N	N	N	N
Nutsedge, yellow	**N**	N	P	P	N	P	N	N	P	N	N	N	N

Source: UC IPM Pest Management Guidelines: Cole Crops (UC ANR Pub. No. 3442).

Notes: C = control; P = partial control; N = no control; — = no information; * - permit required from county agricultural commissioner for purchase or use; color shading: green – improvement of control compared to dacthal, yellow partial loss of control compared to dacthal, complete loss of control compared to dacthal.

Economic Analysis

The economic analysis begins by selecting an herbicide alternative to dacthal for each crop under consideration. Only brassica and allium crops are included in the analysis, due to their large share of dacthal use and limited number of alternative herbicides. We calculate the cost difference between the cost of dacthal and the cost of the alternative on a per-acre basis. Other costs may change when dacthal cannot be used, including herbicide application costs, hand weeding costs, and cultivation costs. When information is available regarding these costs for a crop, we calculate the projected change. Base values for these costs are available for broccoli, dry onion, and cabbage. Similarly, when yield and price information are available for a crop we calculate the projected decline in revenues. Both yield and price information are available for broccoli, dry onion, cabbage, cauliflower, Chinese cabbage, Brussels sprout, kale, leek, kohlrabi, and green onion. We then compute the total change in net revenues estimated for each crop on a per acre basis. Note that **because not all information is available for all crops considered, changes in net revenues per acre cannot be compared across all crops**. This extends to the total changes in net revenues for acreage treated currently with dacthal that would need to use an alternative.

Alternatives selected for economic analysis

As mentioned above, a limited number of herbicides are registered for the crops that utilize dacthal. Table 25 reports the total acreage treated by crop and active ingredient for the 2014-2016 time period. Shaded crop-AI entries are ones for which the AI had no California-registered product as of a July 3, 2018 check of the DPR product label database. In a few instances, applications were reported for unregistered AIs. This could be due to a registration that ended after 2016, a mistaken PUR database entry, or a reported non-label use. There are also a number of empty white cells; these could be due to a product being registered after 2016 or the availability of a less expensive and/or more efficacious product utilizing a different AI.

Table 25. Product Registration Status and Total Acres Treated 2014-16 by Crop and Active Ingredient+

Crop	Dacthal	Bensulide	Oxyfluorfen	Trifluralin	Pendimethalin	Napropamide	Clethodim	Clopyralid	Sulfentrazone	s-Metolachlor
Leek	954		20		228					
Onion, Dry	25,682	16,106	220,394	131	118,086		32,778			92
Onion, Green	457		455		198		325			
Broccoli	64,292	27,091	156,407	26,418	82	24,412	10,954	2,411		
Brussels Sprout	3,655	1,296	415	250		2,480	247			
Cabbage	7,093	3,625	21,835	1,336			956	32	421	56
Cauliflower	8,029	2,207	61,356	4,710		5,147	2,068	98		
Chinese Cabbage (Nappa)	4,706	1,488	9	422	8		12			25
Gai Lon	1,012	367		171						
Kohlrabi	813	778								
Bok Choy	4,210	1,363	17	380						
Kale	1,837	3,466	172	582			424			19
Mustard	1,561	1,635		1,393			125	21		
Rapini	4,047	2,778					3,008			

+ Crop-active ingredient pairs unregistered as of 7/3/18 in DPR's product label database are shaded in grey.

Based on the assessment of efficacy presented in the previous section, plus the availability of alternatives given current product registrations, an alternative AI was selected for each crop. Table 26 reports these selections. A representative product was then selected for each crop-AI pair. **Critically, none of these AIs are direct replacements for dacthal. All have major weaknesses in terms of their management of key weeds**, mainly broadleaves, and many are problematic for rotational crops, with some even having label restrictions. Thus, these alternatives must be paired with greater use of mechanical and hand weeding, incurring the associated increase in production costs.

Table 26. Partial Alternative Active Ingredients to Dacthal by Crop Utilized in Economic Analysis

Crop	**AI**	**Product**	**Comments**
Leek	Pendimethalin	Prowl H_2O	Only registered alternative
Onion, Dry and Green	Pendimethalin	Prowl H_2O	Lots of oxyfluorfen use on dry onion, but does not meet early season needs.
Broccoli, Cabbage, Cauliflower, Chinese (Nappa) Cabbage	Oxyfluorfen	GoalTender	Good for brassica, not onion. Not registered for other brassica crops.
Brussels Sprout	Napropamide	Devrinol	Rotational crop restrictions could be a problem for rotational crops like celery and onion.
Bok Choy, Gai Lon, Kale, Mustard, Mustard Greens, Rapini	Trifluralin	Treflan HFP	Considered a partial replacement due to limited spectrum of control and long-lasting residues.
Bok Choy, Gai Lon, Kale, Mustard, Mustard Greens	Bensulide	Prefar 4-E	Weak, not a substitute but there’s greater use than for trifluralin.
Rapini	Bensulide	Prefar 4-E	Weak, not a substitute but there’s no trifluralin use 2014-2016.
Chinese (Nappa) Cabbage	Bensulide	Prefar 4-E	Weak, not a substitute but there’s virtually no oxyfluorfen use 2014-2016.
Kohlrabi	Bensulide	Prefar 4-E	Weak, not a substitute but it’s the only registered alternative

Pesticide material cost per acre

Calculating the pesticide material cost per acre requires pesticide product prices and application rates per acre.

Price

Table 27 reports the prices for the selected products. All of the products are sold in units of one or more gallons. The table reports the price per gallon and per pound of active ingredient. The latter figure will be used to calculate the pesticide material cost per acre. Prices are from industry sources, cross-referenced with internet searches.

Table 27. Prices for Selected Pesticide Products

Active Ingredient	Product	$/Unit	Unit	Lbs. AI/Unit	$/Lb. AI
Dacthal	Dacthal Flowable	$203.58	Gallon	6	$33.93
Pendimethalin	Prowl H20	$47.98	Gallon	3.8	$12.63
Oxyfluorfen	GoalTender	$162.95	Gallon	4	$40.74
Napropamide	Devrinol 50DF	$12.15	Pound	0.5	$24.30
Trifluralin	Trifluralin 4EC	$37.58	Gallon	4	$9.40
Bensulide	Prefar 4-E	$87.78	Gallon	4	$21.95

Application rate

We compute a three-year average dacthal application rate in pounds of AI per acre for each crop using PUR data (Table 28). For most crops the average application rate was lower than the recommended label rate, consistent with the use of banded applications. (Banding is required for the brassica crops examined here. Allium crops have a partial exemption from banding in certain counties in certain months.)

Table 28. Dacthal Application Rate by Crop: 2014-16 (lbs. AI/acre)

Crop	2014	2015	2016	3-year average
Broccoli	3.51	3.69	3.26	3.48
Onion, Dry	5.15	5.64	5.81	5.55
Cabbage	4.22	4.01	4.17	4.14
Cauliflower	3.15	2.99	2.86	2.99
Chinese Cabbage	4.38	4.99	4.72	4.69
Bok Choy	4.18	4.55	4.64	4.44
Brussels Sprout	5.39	5.62	4.22	4.76
Kale	5.58	5.83	6.04	5.86
Rapini	2.32	2.29	2.34	2.32
Mustard	2.80	6.65	6.17	5.05
Leek	5.16	5.76	6.14	5.77
Gai Lon	4.84	4.31	4.50	4.64
Kohlrabi	4.69	4.56	4.89	4.60
Onion, Green	6.29	5.41	6.00	6.08

We compute a three-year average application rate in pounds of AI per acre for each crop-alternative AI pair using PUR data (Table 29).

Table 29. Application Rate for Alternative Active Ingredient by Crop: 2014-2016 (lbs. AI/acre)

Crop	Alternative	2014	2015	2016	Three-year Average
Broccoli	Oxyfluorfen	0.28	0.28	0.29	0.28
Onion, Dry	Pendimethalin	0.71	0.81	0.74	0.75
Cabbage	Oxyfluorfen	0.38	0.39	0.41	0.39
Cauliflower	Oxyfluorfen	0.31	0.30	0.32	0.31
Chinese Cabbage	Oxyfluorfen	0.32	---	---	0.32
	Trifluralin	0.72	0.86	0.55	0.77
	Bensulide	3.24	3.11	4.26	3.50
Bok Choy	Trifluralin	0.78	0.42	0.98	0.82
	Bensulide	3.99	4.61	0	4.19
Brussels Sprout	Napropamide	0.63	0.88	0.70	0.72
Kale	Trifluralin	0.73	0.64	1.5	1.06
	Bensulide	4.12	4.04	4.00	4.03
Rapini	Trifluralin	---	---	---	---
	Bensulide	5.05	4.97	4.58	4.81
Mustard	Trifluralin	1.5	1.33	2.06	1.62
	Bensulide	3.94	4.38	3.16	3.92
Leek	Pendimethalin	0.99	1.50	0.81	0.92
Gai Lon	Trifluralin	0.55	0.53	0.55	0.54
	Bensulide	2.73	3.1	2.98	2.93
Kohlrabi	Bensulide	5.96	1.18	2.5	1.43
Onion, Green	Pendimethalin	0.79	0.92	0.94	0.80

Pesticide material cost per acre

Utilizing the prices of the pesticide products and the application rate per acre based on the reported pounds of active ingredient applied and treated acres, we compute the pesticide material cost per acre for an application of dacthal and an application of the alternative pesticide product (Table 30). For gai lon, bok choy, kale, mustard, and rapini we utilize the lower of the costs per acre for Prefar-4E and Trifluralin 4EC. The selected alternative for each crop is indicated by boldface type.

Table 30. Pesticide Material Cost Per Acre

Crop	Dacthal Cost	Alternative Product	Alternative Cost	Cost Difference
Broccoli	$118.21	**GoalTender**	**$11.60**	**-$106.61**
Onion, Dry	$188.18	**Prowl H_2O**	**$9.49**	**-$178.69**
Cabbage	$140.63	**GoalTender**	**$15.96**	**-$124.67**
Cauliflower	$101.50	**GoalTender**	**$12.56**	**-$88.94**
Chinese Cabbage	$159.29	GoalTender	$12.84	-$146.45
		Trifluralin 4EC	**$7.23**	**-$152.06**
		Prefar 4-E	$76.81	-$82.48
Bok Choy	$150.71	**Trifluralin 4EC**	**$7.71**	**-$143.00**
		Prefar 4-E	$91.97	-$58.74
Brussels Sprout	$161.38	**Devrinol**	**$17.55**	**-$143.83**
Kale	$198.93	**Trifluralin 4EC**	**$9.94**	**-$188.99**
		Prefar 4-E	$88.55	$88.55
Rapini	$78.67	Trifluralin 4E	N/A	N/A
		Prefar 4-E	**$105.53**	**$26.86**
Mustard	$171.19	**Trifluralin 4EC**	**$41.00**	**-$130.19**
		Prefar 4-E	$63.92	-$107.27
Leek	$195.90	**Prowl H_2O**	**$11.62**	**-$184.28**
Gai Lon	$157.45	**Trifluralin 4EC**	**$5.09**	**-$152.36**
		Prefar 4-E	$64.26	-$93.19
Kohlrabi	$156.14	**Prefar 4-E**	**$31.33**	**-$124.81**
Onion, Green	$206.40	**Prowl H_2O**	**$10.12**	**-$196.28**

As Table 30 shows, for most crops the alternative pesticide product costs less per acre than dacthal. The two exceptions are Prefar 4-E on kale and rapini. Given the significant use of dacthal on most of the crops in the table, this suggests that differences in other costs, including weeding costs, and differences in yield are important factors in growers' decision to use dacthal. Though trifluralin is relatively inexpensive and controls grasses well, it provides weak control of broadleaves, which are the primary weeds.

No acreage or yield information is available for bok choy, rapini, mustard or gai lon, so the economic analysis is limited to evaluating the change in the pesticide material cost per acre.

Application costs

There are two key considerations when determining whether or not a change in application cost is a necessary component of the analysis. First, if alternatives are also included in a tank mix like dacthal often is, then the base cost of application is unchanged because the other pesticides must still be applied. While dacthal applied alone or with an adjuvant is more common than any other tank mix, overall a substantial share of dacthal is applied with one or more other active ingredients. Second, if alternatives are applied in a different manner or at different stages of plant development then application costs will differ. Napropamide (Devrinol), trifluralin (Treflan) and oxyfluorfen (GoalTender) are all groundspray applied like dacthal. Pendimethalin (Prowl) on allium crops is mostly groundspray applied, although chemigation may also be used. Bensulide is groundspray applied in Monterey County, while sometimes it is applied via chemigation in Imperial.

While the above information indicates that there are some exceptions, we assume that application costs are the same for dacthal and the alternatives considered. One reason we do so is that the application method for ground-applied materials other than fumigants is not specified in the PUR data, so there is no way to determine the extent to which chemigation is used. In addition, insecticides are the most commonly used co-products in tank mixes with dacthal. The most commonly used insecticides appear to be available for use with the alternative herbicide products, so the base costs of these applications could be unchanged. Either these mixtures have been observed in the PUR records, or they are allowed based on an analysis of the product labels (Dow AgroSciences 2014b, 2014c, 2014e, 2015; BASF Corporation 2006, 2015, 2016; Loveland Products 2014; United Phosphorus, Inc. 2015).

Weeding costs: hand weeding and cultivation

As noted earlier, for commercially acceptable weed control, for all of the crops that use dacthal, cultural and physical weed control tools are currently needed in addition to the herbicide. In the absence of herbicide availability, one proxy for weeding costs is the difference in costs between organic and conventional production of a given crop. In expectation, weeding costs should increase by no more than they would under an organic weed management program where only mechanical and hand weeding are used. Organic broccoli had 169 percent higher hand weeding costs than conventional broccoli in a pair of 2004 UC cost studies (Smith et al. 2004, Tourte et al. 2004). Comparable numbers are not available for the other crops considered. Organic lettuce had 163 percent higher hand weeding costs than conventional lettuce in a pair of 2009 UC cost studies (Tourte et al. 2009, Smith et al. 2009). Although lettuce has a different production system and is not considered here, the similar increase provides support for including a case with a 166 percent increase in weeding costs. In contrast, while cultivation costs are unchanged for broccoli, cultivation costs increase by 71 percent for organic lettuce compared to conventional lettuce. Lati et al. (2016) found a 156 percent increase in hand weeding costs when comparing an untreated control to dacthal.

Estimating the change in weeding costs due to substituting a partial chemical replacement for dacthal is more complex. It will depend on the relative efficacies of the herbicides and the composition and level of the weed population. Accordingly, we provide a range of values between no increase in cost and the increase in cost for organic production compared to conventional production. UC Cooperative Extension personnel estimate an increase in hand weeding time of roughly 30 to 60 percent, depending on the crop. We use a 40 percent increase to represent this range.

For the three crops with available cost studies, Table 31 reports the base values and Table 32 reports the range of changes in weeding costs. Hand weeding costs are hours of weeding time reported in the cost studies for onion (Wilson et al. 2016) and cabbage (Takele, Daugovish and Vu 2012) multiplied by the hourly wage plus benefits of $16.90 used in the 2017 UC cost study for broccoli (Tourte et al. 2017). While the broccoli and cabbage studies were for coastal production areas, it is important to keep in mind that the onion cost study was prepared for onions for dehydration in the Intermountain Region and weed management costs may differ substantially across production regions and intended crop use. Despite the caveat, personal communications with UC Cooperative Extension personnel suggest that weeding costs are similar for dry onions raised to be sold whole and onions raised for dehydration.

Table 31: Weeding Costs Per Acre: Broccoli, Onion and Cabbage

	Broccoli	**Dry Onion**	**Cabbage**
Hand weeding	$150	$254	$120
Cultivation	$86	$8	$15
Total	$236	$262	$135

Sources: Tourte et al. (2017), Wilson et al. (2016), Takele, Daugovish and Vu (2012)

Using the base values reported in Table 31, Table 32 presents the increase in weeding costs associated with each combination of percentage increases in hand weeding and cultivation costs.

Table 32. Increase in Weeding Costs Per Acre Based on Percentage Increases in Hand Weeding and Cultivation Costs: Broccoli, Onion and Cabbage

	----Cultivation cost----	
Hand weeding cost	0%	71%
Broccoli		
0%	$0	$61
40%	$60	$121
156%	$235	$296
166%	$250	$311
Dry Onion		
0%	$0	$6
40%	$101	$107
156%	$395	$401
166%	$421	$426
Cabbage		
0%	$0	$11
40%	$48	$59
156%	$187	$198
166%	$199	$210

Yield losses

Based on UC Cooperative Extension estimates and the scientific literature, we consider two potential percentage yield losses: 10 percent and 20 percent. If additional hand and mechanical weeding were used exclusively instead of dacthal, yield losses would likely be at least ten percent owing to the increased need for cultivation and hand weeding, which will damage the delicate crop feeder roots. In winter, yield losses would be larger, as rainy wet fields are impossible to cultivate or hand weed, so weeds will grow and compete. On the other hand, residual herbicides, like dacthal, provide protection for weeks after application, even during prolonged rain.

Based on a pair of 2004 UC cost studies for broccoli, the difference between organic and conventional yields is 2 percent (Smith et al. 2004, Tourte et al 2004). Accordingly, we also include an estimate for a zero percent loss.[6] However, broccoli is a robust crop with planting techniques such as use of transplants that mean the yield effects of increased soil disturbance from cultivation and hand weeding are small. As noted above, it is difficult to generalize across crops due to the wide variety of crop densities, market sector such as baby greens and many other variations in cropping. Other crops considered, such as bok choy, collards green onion and rapini, have much closer plantings and would sustain significantly more damage from increased reliance on cultivation and hand weeding. Expected yield losses when a different herbicide is used vary by the herbicide and the crop. Where oxyfluorfen can be used in broccoli and cauliflower, for example, there will likely be no yield loss. Other crops like gai lon, green onion and radish with fewer registered herbicides available are likely to sustain larger yield losses due to reduced efficacy and increased need for cultivation and hand weeding. Overall, we estimate that yields would decline by roughly 10 percent.

Two recent meta-analysis studies estimate the crop yield gap between organic and conventional agriculture over a number of crops and regions. Based on their conclusions, we also consider a 20 percent yield loss scenario. de Ponti, Rijk and van Ittersum (2012) examined 362 studies from 1984-2010 which conducted a comparative analysis of conventional and organic yields at the field- and crop-level. They found that, on average, organic yields were 80 percent of conventional yields, where the yield gap varied significantly depending on the crop and region. For vegetables, 74 studies had an average relative yield of 80 percent with studies from a range of regions/countries including Europe, Canada, Argentina, Turkey, and the US (pg. 4). Identified in in the analysis were: carrots with a relative yield of 89 percent (n=7), lettuce 86 percent (n=6), and tomato 81 percent (n=20). For 18 other vegetable crops, mostly from North America and Europe (n=40, including cabbage n=5, onions n=5, bell pepper n=4, and bok choi n=4), organic yields were 77 percent of conventional yields on average. Ponisio et al. (2015) used an updated dataset and meta-analytic empirical methodology to incorporate a hierarchal structure into their analysis. On average, they found that organic yields were 81 percent of conventional yields, with a 95 percent confidence interval of ±3.7 percent. The average organic vegetable yield (n=20) was slightly higher than overall average, but also with a wider 95 percent confidence interval. Ponisio et al. (2015) also show that, all other things equal, organic yield gaps decrease in polyculture systems, when there are more crops in a rotation, and when more organic nitrogen inputs are used. Taking these two meta-analyses together, a conservative interpretation would be that organic vegetable yields would be roughly 75 to 85 percent of conventional yields.

[6] Note that for crops with only yield and price data available, the 0 percent estimates will correspond to the difference in herbicide material costs.

A note on industry quantity and price

Generally organic produce receives a price premium relative to produce grown conventionally. This premium helps to offset the revenue reduction due to lower organic yields. In this case, however, no such premium would be obtained in the absence of organic certification.

Price would only respond to a change in quantity if the industry-level demand for a California crop 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.

Many of the crops here are very minor ones that have multiple close substitutes for consumers. At least during some parts of the year, Arizona and/or Mexico are competing producers. Furthermore, not all acreage of these crops utilizes dacthal as part of a weed management program, 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.

For the purposes of this analysis, we assume that demand for these California crops is perfectly elastic, so that price does not change in response to a change in the quantity produced. To the extent that there is a price response, estimated losses will be reduced.

Gross revenue losses per acre by crop

The reduction in gross revenues per acre due to the loss of dacthal depends on the crop's price and base yield. Because prices are assumed to remain constant, gross revenue losses are proportional to yield losses. Table 33 reports gross revenue reductions per acre for the studied crops for which yield and price information are available (CDFA 2017). On a per acre basis, the three crops for which cost study information is available (broccoli, dry onion and cabbage) have relatively small gross revenue losses. Only kohlrabi has a lower one. Losses were largest for green onion, owing to its high value per acre.

Table 33. Change in Gross Revenue Losses per Acre by Crop and Percentage Yield Loss

Crop	-10%	-20%
Broccoli	-$668	-$1,335
Onion, Dry	-$662	-$1,323
Cabbage	-$844	-$1,688
Cauliflower	-$858	-$1,715
Chinese Cabbage	-$927	-$1,854
Brussels Sprout	-$1,408	-$2,816
Kale	-$1,422	-$2,844
Leek	-$1,467	-$2,933
Kohlrabi	-$618	-$1,236
Onion, Green	-$2,355	-$4,710

Changes in net returns per acre by crop

The base for analyzing the change in net returns is dependent on available information. Only information on price, yield, and pesticide costs are available for seven of the crops we address. Table 34 reports the decrease in projected net returns for yield reductions of 10 percent and 20 percent for only these seven crops. If yields do not decline, the change in net returns will simply be the change in the pesticide material cost reported in Table 30. Again, losses are largest for green onion, due to its high value per acre. For green onion, as well as some other crops, net revenue losses are smaller in magnitude than gross revenue losses because the per acre cost of the alternative herbicide is lower.

Table 34. Change in Net Returns per Acre by Crop and Percentage Yield Loss

Crop	-10%	-20%
Cauliflower	-$769	-$1,626
Chinese Cabbage	-$780	-$1,707
Brussels Sprout	-$1,264	-$2,673
Kale	-$1,233	-$2,655
Leek	-$1,282	-$2,749
Kohlrabi	-$493	-$1,111
Onion, Green	-$2,159	-$4,513

Because information on hand weeding and cultivation costs is available for broccoli, onion and cabbage, the partial budget analysis can include effects on these costs as well. Table 35 presents estimates of the change in per acre net revenues as a function of the percentage changes in yield, pesticide cost, hand weeding costs, and cultivation costs. In most scenarios, net returns per acre decline. However, there are seven scenarios under which net returns increase. This occurs because the alternative herbicide costs less per acre than dacthal. When yield declines and cost increases are sufficiently small, the reduction in herbicide costs outweighs them.

A number of scenarios are provided for the three crops in Table 35. Based on existing information, some scenarios are more likely than others. Specifically, some scenarios rely on information comparing conventional and organic yields, while others take the use of alternatives into account. For broccoli, recall that the organic and conventional cost studies had the same cultivation cost. Considering the 40 percent increase in hand weeding costs scenario, net revenues per acre would decrease by $834 (10 percent yield loss). Under the same scenario, net returns per acre for cabbage would decline by $1,017. For onion, early season cultivation and hand weeding costs are likely to increase, the latter by 40 to 60 percent. For onion, considering the 40 percent increase in hand weeding costs, and referencing the 71 percent increase in cultivation costs between organic and conventional lettuce cost studies, net returns per acre would decline by $590 (10 percent yield loss).

Table 35. Change in Net Returns per Acre for Broccoli, Onion and Cabbage by Percentage Yield Loss and Hand Weeding and Cultivation Cost Increases

	Cultivation costs					
	0%	**71%**	**0%**	**71%**	**0%**	**71%**
Hand weeding costs	Broccoli		Dry onion		Cabbage	
			Yield change = 0%			
0%	$107	$46	$179	$173	-$125	-$135
40%	$46	-$15	$77	$72	-$173	-$183
156%	-$128	-$189	-$217	-$222	-$312	-$323
166%	-$143	-$204	-$242	-$248	-$324	-$335
			Yield change = -10%			
0%	-$774	-$835	-$483	-$489	-$969	-$979
40%	-$834	-$896	-$584	-$590	-$1,017	-$1,027
156%	-$1,009	-$1,070	-$878	-$884	-$1,156	-$1,166
166%	-$1,024	-$1,085	-$904	-$910	-$1,168	-$1,178
			Yield change = -20%			
0%	-$1,442	-$1,503	-$1,145	-$1,150	-$1,812	-$1,823
40%	-$1,502	-$1,563	-$1,246	-$1,252	-$1,860	-$1,871
156%	-$1,677	-$1,738	-$1,540	-$1,546	-$2,000	-$2,010
166%	-$1,692	-$1,753	-$1,566	-$1,571	-$2,012	-$2,022

While this analysis utilizes a partial budgeting approach, the information available in the cost studies enables the calculation of how important these changes in net revenue are compared to overall net revenue per acre. Table 36 shows the change in net returns per acre for broccoli, dry onion, and cabbage under the most likely scenario for each relative to the baseline where dacthal is available. Baseline returns are calculated by computing gross returns per acre (yield multiplied by price) and subtracting cultivation and harvesting costs. These costs were obtained from the UC cost studies (Takele, Daugovish and Vu 2012; Tourte et al. 2017; Wilson et al. 2016).

The baseline net return for broccoli was -$1,342 per acre, so the average broccoli grower was making a loss in 2017. This is consistent with the Tourte et al. (2017) cost study, where growers only received a positive net return under high price and yield scenarios. Under the most likely scenario in this study, net returns decrease by 62 percent. The net returns for onion decrease from $4,006 to $3416 per acre, a decline of fifteen percent. The net returns for cabbage decrease from $1,199 to $182, a decline of 85 percent. The deregistration of dacthal will have the largest impact on net returns for cabbage and broccoli growers.

Table 36: Change in Net Returns per Acre Relative to Baseline for Most Likely Scenarios: Broccoli, Onion and Cabbage

	Baseline net return	**Change in net return**	**Net return under most likely scenario**	**Percentage Change**
Broccoli	-$1,342	-$834	-$2,158	-62%
Onion	$4,006	-$590	$3,416	-15%
Cabbage	$1,199	-$1,017	$182	-85%

Change in net returns by crop: California

We evaluate the change in total net returns by crop based on the annual average treated acreage for 2014-16 (Table 25), and the net returns per acre (Table 34 and Table 35).

The total net returns for the seven crops with no cultivation and hand weeding costs are presented in Table 37 for yield loss scenarios of 10 and 20 percent. For these seven crops, calculated losses range from $6.4 million to $13.9 million. Treated acreage is a significant determinant of the total reduction in net returns for each crop. Examining the crops, which are listed in order of decreasing treated acreage, there is only one deviation in the order of declining losses: green onion has larger losses than kohlrabi. The larger total net revenue loss is associated with larger losses in gross revenue per acre.

Table 37. Changes in Total Net Returns by Crop ($ Million): California

Crop	**-10%**	**-20%**
Cauliflower	-$2.1	-$4.4
Chinese Cabbage	-$1.2	-$2.7
Brussels Sprout	-$1.5	-$3.3
Kale	-$0.8	-$1.6
Leek	-$0.4	-$0.9
Kohlrabi	-$0.1	-$0.3
Onion, Green	-$0.3	-$0.7
Total	-$6.4	-$13.9

Table 38 presents changes in total net revenues for broccoli, onion, and cabbage as a function of the percentage changes in yield, pesticide cost, hand weeding costs, and cultivation costs. The reductions in total net revenues corresponding to the specific scenarios identified in the discussion of Table 35 are $17.9 million for broccoli, $2.4 million for cabbage, and $5.1 million for onion, totaling $25.4 million.

Table 38. Change in Net Returns for Broccoli, Onion and Cabbage by Percentage Yield Loss and Hand Weeding and Cultivation Cost Increases ($ Million): California

	Cultivation cost					
	0%	**71%**	**0%**	**71%**	**0%**	**71%**
Hand weeding cost	Broccoli		Dry onion		Cabbage	
			Yield change = 0%			
0%	$2.3	-$1.0	$1.5	$1.5	-$0.3	-$0.-3
40%	$1.0	-$0.3	$0.7	$0.6	-$0.4	-$0.4
156%	-$2.7	-$4.1	-$1.9	-$1.9	-$0.7	-$0.7
166%	-$3.1	-$4.4	-$2.1	-$2.1	-$0.8	-$0.8
			Yield change = -10%			
0%	-$16.6	-$17.9	-$4.1	-$4.2	-$2.3	-$2.3
40%	-$17.9	-$19.2	-$5.0	-$5.1	-$2.4	-$2.4
156%	-$21.6	-$22.9	-$7.5	-$7.6	-$2.7	-$2.8
166%	-$21.9	-$23.3	-$7.7	-$7.8	-$2.8	-$2.8
			Yield change =-20%			
0%	-$30.9	-$32.3	-$9.8	-$9.8	-$4.3	-$4.3
40%	-$32.3	-$33.5	-$10.7	-$10.7	-$4.4	-$4.4
156%	-$35.9	-$37.2	-$13.2	-$13.2	-$4.7	-$4.7
166%	-$36.3	-$37.6	-$13.4	-$13.5	-$4.8	-$4.8

Changes in net returns by crop: Monterey, Santa Barbara, and San Luis Obispo counties

Because high concentration of dacthal degradates were detected in the Salinas Valley and in the Santa Maria area, we also evaluate changes in net returns by crop in Monterey, Santa Barbara, and San Luis Obispo counties. We utilize county-level acreage treated with dacthal and the state-level price and yield information discussed previously.

Monterey County. Table 39 reports the total changes in net returns by crop for Monterey County for crops with only pesticide cost and gross revenue information available. Unlike the state as a whole, total net return losses are not primarily driven by acres treated. Crops in the table are listed in order of statewide treated acres; for Monterey County, in decreasing order of treated acreage, the crop list is cauliflower, kale, Chinese cabbage, Brussels sprout, green onion, leek and kohlrabi. Kohlrabi acreage was negligible, resulting in negligible annual losses. Relatively high gross revenues per acre for kale, Brussels sprout and leek (all above $14,000 per acre) increase total losses relative to lower-valued crops with more treated acres. Although green onion has the highest gross revenue per acre (over $23,000), its small treated acres result in relatively small net revenue losses compared to other crops in the table. With the exception of cauliflower, losses per crop in Monterey County would be under $0.5 million with a 20 percent yield loss. If all seven crops sustained a 20 percent yield loss, the aggregate reduction in net returns would be roughly $5.2 million.

Table 39. Changes in Net Returns by Crop ($ Million): Monterey County

Crop	**-10%**	**-20%**
Cauliflower	-$1.8	-$3.8
Chinese Cabbage	-$0.1	-$0.3
Brussels Sprout	-$0.2	-$0.4
Kale	-$0.1	-$0.1
Leek	-$0.2	-$0.4
Kohlrabi	$0.0	$0.0
Onion, Green	-$0.1	-$0.2
Total	-$2.5	-$5.2

Table 40 presents changes in total net revenues for Monterey County for broccoli, onion and cabbage as a function of the percentage changes in yield, pesticide cost, hand weeding costs, and cultivation costs. The reductions in total net revenues corresponding to the specific scenarios identified in the discussion of Table 35 are $12.7 million for broccoli, $0.5 million for cabbage, and $1.2 million for onion, totaling $14.4 million.

Table 40. Change in Net Returns for Broccoli, Onion and Cabbage by Percentage Yield Loss and Hand weeding and Cultivation Cost Increases ($ Million): Monterey

	Cultivation cost					
	0%	**71%**	**0%**	**71%**	**0%**	**71%**
Hand weeding cost	Broccoli		Dry onion		Cabbage	
			Yield change = 0%			
0%	$1.6	$0.7	$0.4	$0.4	-$0.1	-$0.1
40%	$0.7	-$0.2	$0.2	$0.2	-$0.1	-$0.1
156%	-$2.0	-$2.9	-$0.5	-$0.5	-$0.2	-$0.2
166%	-$2.2	-$3.1	-$0.5	-$0.5	-$0.2	-$0.2
			Yield change = -10%			
0%	-$11.8	-$12.7	-$1.0	-$1.0	-$0.5	-$0.5
40%	-$12.7	-$13.7	-$1.2	-$1.2	-$0.5	-$0.5
156%	-$15.4	-$16.3	-$1.9	-$1.9	-$0.6	-$0.6
166%	-$15.6	-$16.5	-$1.9	-$1.9	-$0.6	-$0.6
			Yield change =-20%			
0%	-$22.0	-$22.9	-$2.4	-$2.4	-$1.0	-$1.0
40%	-$22.9	-$23.8	-$2.6	-$2.6	-$1.0	-$1.0
156%	-$25.6	-$26.5	-$3.2	-$3.3	-$1.1	-$1.1
166%	-$25.8	-$26.7	-$3.3	-$3.3	-$1.1	-$1.1

Santa Barbara County. No dacthal applications to dry onion, cabbage or green onion were reported in Santa Barbara County, and applications to leek were negligible over the three-year period. As shown in Table 41, decreases in net returns for the remaining crops for which only revenues and pesticide cost information were available are relatively small, due to limited treated acres (Table 4). If the five crops considered in the table sustained 20 percent yield losses, the aggregate reduction in net returns would be roughly $2.4 million. Only Brussels sprout shows a projected net revenue decrease of over $1 million with a 20 percent revenue loss.

Table 41. Changes in Net Returns by Crop ($ Million): Santa Barbara County

Crop	**-10%**	**-20%**
Cauliflower	-$0.1	-$0.1
Chinese Cabbage	-$0.3	-$0.6
Brussels Sprout	-$0.5	-$1.1
Kale	-$0.1	-$0.3
Kohlrabi	-$0.1	-$0.3
Total	-$1.1	-$2.4

Of the three crops with weed management cost information available, Santa Barbara County reported acreage treated with dacthal only for broccoli. Broccoli (Table 42) shows very small losses due to the small number of acres treated with dacthal. With a 20 percent yield loss and the maximum increases in hand weeding costs (166 percent) and cultivation costs (71 percent), losses to broccoli would be slightly under $0.5 million.

Table 42. Changes in Net Returns to Broccoli by Percentage Yield Loss and Hand Weeding and Cultivation Cost Increases ($ Million): Santa Barbara County

	Cultivation cost	
Hand weeding cost	0%	71%
Yield change = 0%		
0%	$0.0	$0.0
40%	$0.0	-$0.0
156%	-$0.0	-$0.1
166%	-$0.0	-$0.1
Yield change = -10%		
0%	-$0.2	-$0.2
40%	-$0.2	-$0.3
156%	-$0.3	-$0.3
166%	-$0.3	-$0.3
Yield change =20%		
0%	-$0.4	-$0.4
40%	-$0.4	-$0.4
156%	-$0.5	-$0.5
166%	-$0.5	-$0.5

San Luis Obispo County. No acreage treated with dacthal was reported in San Luis Obispo County for kohlrabi or green onion. Table 43 reports the total changes in net revenues for the remaining crops for which only gross revenue and pesticide cost information were available. Cauliflower, kale and leek had an average of fewer than 100 acres treated annually with dacthal, which was the primary determinant of the relatively small county-level net returns losses. Chinese cabbage and Brussels sprout had larger treated acreages.

Table 43. Changes in Net Returns by Crop ($ Million): San Luis Obispo

Crop	-10%	-20%
Cauliflower	-$0.1	-$0.1
Chinese Cabbage	-$0.6	-$1.2
Brussels Sprout	-$0.4	-$0.8
Kale	-$0.1	-$0.1
Leek	$0.0	-$0.1
Total	-$1.2	-$2.3

Table 44 presents changes in total net revenues for San Luis Obispo County for broccoli, onion and cabbage as a function of the percentage changes in yield, pesticide cost, hand weeding costs, and cultivation costs. The reductions in total net revenues corresponding to the specific scenarios identified in the discussion of Table 35 are $0.1 million for broccoli, $0.0 million for cabbage, and $0.0 million for onion, totaling $0.1 million.

Table 44. Change in Net Returns for Broccoli, Onion and Cabbage by Percentage Yield Loss and Handweeding and Cultivation Cost Increases ($ Million): San Luis Obispo

	Cultivation cost					
	0%	**71%**	**0%**	**71%**	**0%**	**71%**
Handweeding cost	Broccoli		Dry onion		Cabbage	
	Yield change = 0%					
0%	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0
40%	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0
156%	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0
166%	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0
	Yield change = -10%					
0%	-$0.1	-$0.1	$0.0	$0.0	$0.0	$0.0
40%	-$0.1	-$0.1	$0.0	$0.0	$0.0	$0.0
156%	-$0.1	-$0.1	$0.0	$0.0	$0.0	$0.0
166%	-$0.1	-$0.1	$0.0	$0.0	$0.0	$0.0
	Yield change =20%					
0%	-$0.1	-$0.1	$0.0	$0.0	-$0.1	-$0.1
40%	-$0.1	-$0.1	$0.0	$0.0	-$0.1	-$0.1
156%	-$0.1	-$0.2	$0.0	$0.0	-$0.1	-$0.1
166%	-$0.1	-$0.2	$0.0	$0.0	-$0.1	-$0.1

Caveats and limitations

There are a number of caveats and limitations regarding this analysis, apart from the standard considerations accompanying any partial budget analysis. Significant ones are discussed below.

Data availability was an important limitation for the scope of this analysis. While treated acreage, application rates, and pesticide product prices were available for all crops considered, other information was not (Table 45). Among the fourteen brassica and allium crops with the largest average annual acreage treated with dacthal for the 2014-16 period, information on hand weeding and cultivation costs was available only for three. Of the remaining eleven, yield and price information were reported by CDFA for only seven. For the remaining four crops, no yield or price was reported by CDFA, although the USDA's Agricultural Marketing Service (AMS) reported shipping point or terminal market prices for them. In the absence of yield information, however, gross revenues could not be calculated. At the county level, many of these crops were reported in an aggregated category, "miscellaneous crops" in Santa Barbara and San Luis Obispo counties, so even less information was available.

Table 45. Summary of Available Data by Crop: California

Crop	Hand weeding cost ($/acre)	Cultivation cost ($/acre)	Yield (tons/acre)	Price ($/ton)
Broccoli	$150	$86	6.73	$992
Onion, Dry	$254	$8	24.91	$266
Cabbage	$120	$15	21.06	$401
Cauliflower			9.61	$892
Chinese Cabbage			24.34	$381
Brussels Sprout			10.78	$1,306
Kale			10.06	$1,414
Leek			14.05	$1,044
Kohlrabi			6.30	$981
Onion, Green			15.59	$1,511
Bok Choy*				$880
Rapini**				$3,700
Mustard**				$1,240
Gai Lon**				$2,015

*AMS shipping point price

**AMS average of Los Angeles and San Francisco terminal market prices

The variation in the types of information available across crops leads to the caveat that not only are some crops that use dacthal omitted, but even for those crops that are included, the projected losses cannot be compared across all crops. While information on weeding costs was not available for some crops, weeding costs would increase if an alternative pesticide or hand weeding and mechanical cultivation alone were used. There is simply no information regarding current weeding costs that would allow the change in weeding costs to be computed. However, we do aggregate costs across the crops with the same sets of price, cost, and yield information.

As discussed earlier, a key assumption of the gross revenue computation is that price will not change in response to the change in the quantity produced due to the yield loss associated with dacthal. To the extent that price increases, the losses calculated here are overestimates. A related assumption is that there is not a substantial reduction in acreage of a crop due to the inability to treat with dacthal if needed. If there was a substantial decrease, then it would be more likely that price would increase. This would reduce per acre losses and, consequently, total net revenue losses. However, the decline in acreage would increase total net revenue losses for the crop, so the net effect is indeterminate *ex ante*.

We utilized the difference in yields between organically and conventionally grown crops in the scientific literature as a measure for evaluating the yield losses potentially due to being unable to treat with dacthal. Because conventional production systems can use an alternative pesticide, this estimate is likely to be an overestimate. Accordingly, we utilize an estimate provided by UC Cooperative Extension personnel as well. Similarly, we utilize the differences in weeding costs between conventional and organic production in UC cost studies when available as one measure of the increase in costs, and pair it with an estimate from UC Cooperative Extension personnel.

Another caveat is that we specified a single alternative for each crop. In practice, specific weed problems will influence growers' choice of an alternative pesticide. Further, the tank mix analysis indicates that growers often include other products with dacthal. If growers determine that two or more products are necessary if they cannot use dacthal, then pesticide material costs will increase, and net returns decrease. Similarly, based on the available information we assumed that there will be no change in application costs.

Some of the alternative pesticides restrict crop rotation options. Limiting rotation options can lower overall net returns to farming operations. Any such effects are not included in this crop-level analysis.

Other Approaches

Banning the use of dacthal regionally or statewide would reduce net revenues for brassica and allium crops in California. The regulatory motivation for evaluating critical uses of dacthal was the detection of its degradates in groundwater as a result of legal agricultural use. There are tools apart from a ban that may mitigate groundwater contamination. First, a limited ban or additional use regulations could focus on areas where high levels of degradates have been found, rather than a state-level deregistration. Second, dacthal could be added to DPR's groundwater protection list and new GWPAs could be created in order to reduce leaching potential and enhance monitoring and oversight.

Another approach is that the enhancement of existing alternatives, such as the use of automated cultivators to reduce hand weeding costs, could mitigate the effects of a ban (Lati et al. 2016). The addition of alternatives that are more efficacious than those currently available could also mitigate the effects. 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.

Appendix

This appendix reports county-level frequencies of herbicide use by crop in Monterey, San Luis Obispo, and Santa Barbara counties for 2014 to 2016 in Table 46 to Table 54. In each table, the product column contains the name of the herbicide product used. The active ingredient column gives the name of the active ingredient in the product. For the products with multiple active ingredients, each active ingredient is listed on its own line. The frequency column reports the number of fields receiving an application of the product. A field is defined as a unique combination of the *grower_id* and *site_loc_id* variables in the PUR dataset. Acres treated measures the number of acres the product was applied to. It does not account for tank mixes. A tank mix of Dacthal and Prefar 4-E applied to one acre would be counted as one acre treated for both products. Pounds AI reports the total pounds of active ingredient in the product from all applications to the crop.

Table 46. Herbicides Used on Fields in Monterey by Crop: 2014

Crop	Product	Active Ingredient	Fields	Acres	Lbs. AI
Bok Choy	Dacthal	Chlorthal-Dimethyl	43	65	204
	Prefar 4-E	Bensulide	16	51	198
	Shark EW	Carfentrazone-Ethyl	2	5	0
Broccoli	Dacthal	Chlorthal-Dimethyl	1,494	16,376	39,320
	GoalTender	Oxyfluorfen	989	10,047	2,166
	Prefar 4-E	Bensulide	470	5,178	12,987
	Devrinol 50-DF	Napropamide	86	906	353
	Galigan 2E	Oxyfluorfen	13	121	44
	Gramoxone SL 2.0	Paraquat Dichloride	5	65	22
	Triflurex	Trifluralin	2	29	13
	Arrow 2 EC	Clethodim	2	20	3
	Devrinol DF-XT	Napropamide	1	15	4
	Galigan H2O	Oxyfluorfen	1	5	1
Brussels	Prefar 4-E	Bensulide	18	241	461
	Triflurex	Trifluralin	18	196	200
	Dacthal	Chlorthal-Dimethyl	11	81	260
	Devrinol 50-DF	Napropamide	5	16	4
Cabbage	GoalTender	Oxyfluorfen	95	631	137
	Dacthal	Chlorthal-Dimethyl	75	481	1,128
	Galigan 2E	Oxyfluorfen	2	42	19
	Prefar 4-E	Bensulide	2	18	43
Cauliflower	GoalTender	Oxyfluorfen	394	3,867	1,118
	Dacthal	Chlorthal-Dimethyl	216	2,109	6,083
	Prefar 4-E	Bensulide	41	406	1,022

Crop	Product	Active Ingredient	Fields	Acres	Lbs. AI
	Galigan 2E	Oxyfluorfen	22	202	48
	Galigan H2O	Oxyfluorfen	2	24	3
	Gramoxone SL 2.0	Paraquat Dichloride	1	12	2
Chinese Cabbage	Dacthal	Chlorthal-Dimethyl	49	135	372
	Prefar 4-E	Bensulide	16	75	281
Kale	Prefar 4-E	Bensulide	72	372	1,363
	Dacthal	Chlorthal-Dimethyl	19	94	231
	Kerb SC	Propyzamide	1	2	2
Kohlrabi	Dacthal	Chlorthal-Dimethyl	1	0	1
Leek	Dacthal	Chlorthal-Dimethyl	29	90	224
Lettuce, Head	Kerb SC	Propyzamide	1,683	19,138	11,567
	Prefar 4-E	Bensulide	524	5,677	14,617
	Shark EW	Carfentrazone-Ethyl	145	1,421	8
	Kerb 50-W	Propyzamide	57	583	329
	Balan	Benefin	55	658	404
	Kerb 50-W	Propyzamide	17	159	58
	Roundup Powermax	Glyphosate, Potassium Salt	9	146	404
	K-Pam HL	Potassium N-Methyldithiocarbamate	2	101	34,679
	Goal 2XL	Oxyfluorfen	2	67	17
	Poast	Sethoxydim	1	6	2
	Dacthal	Chlorthal-Dimethyl	1	5	9
Mustard, (Mizuna)	Prefar 4-E	Bensulide	79	167	479
	Dacthal	Chlorthal-Dimethyl	1	5	19
Onion (Not Green)	GoalTender	Oxyfluorfen	157	2,849	636
	Dacthal	Chlorthal-Dimethyl	121	2,077	12,441
	Maestro 4EC	Bromoxynil Octanoate	43	795	167
		Bromoxynil Heptanoate			161
	Outlook	Dimethenamid-P	36	694	47
	Prowl H2O	Pendimethalin	31	627	594
	Maestro 2EC	Bromoxynil Octanoate	25	484	238
	Galigan 2E	Oxyfluorfen	13	233	49
	Goal 2XL	Oxyfluorfen	4	63	9
	Gramoxone Sl	Paraquat Dichloride	1	55	76
Onions (Green)	Dacthal	Chlorthal-Dimethyl	4	21	93

Crop	Product	Active Ingredient	Fields	Acres	Lbs. AI
Pre-plant	Goal 2XL	Oxyfluorfen	287	3,253	980
	Dacthal	Chlorthal-Dimethyl	33	342	507
	Trifluralin HF	Trifluralin	22	250	92
	Roundup Powermax	Glyphosate, Potassium Salt	6	49	94
	Gly Star Plus	Glyphosate, Isopropylamine Salt	1	10	82
	ET	Pyraflufen-Ethyl	1	2	0

Source: Authors' calculations derived from the CDPR Pesticide Use Reporting Database

Table 47. Herbicides Used on Fields in Monterey by Crop: 2015

Crop	Product	Active Ingredient	Fields	Acres	Lbs. AI
Bok Choy	Dacthal	Chlorthal-Dimethyl	38	80	275
	Prefar 4-E	Bensulide	27	52	153
Broccoli	Dacthal	Chlorthal-Dimethyl	1,231	14,104	35,213
	GoalTender	Oxyfluorfen	922	9,650	2,368
	Prefar 4-E	Bensulide	423	4,413	12,578
	Devrinol 50-DF	Napropamide	74	652	253
	Devrinol DF-XT	Napropamide	22	233	46
	Galigan H2O	Oxyfluorfen	20	237	44
	Goal 2XL	Oxyfluorfen	19	201	78
	Galigan 2E	Oxyfluorfen	18	186	73
	Gramoxone SL 2.0	Paraquat Dichloride	11	89	102
	Trifluralin HF	Trifluralin	6	41	20
	Triflurex	Trifluralin	3	26	12
	Poast	Sethoxydim	3	7	2
	Kerb SC	Propyzamide	2	25	12
	Select Max	Clethodim	2	20	2
	Arrow 2 EC	Clethodim	2	20	3
	Shark EW	Carfentrazone-Ethyl	1	2	0
Brussels sprout	Dacthal	Chlorthal-Dimethyl	18	186	585
	Prefar 4-E	Bensulide	12	131	390
	Select Max	Clethodim	2	33	4
	Shark EW	Carfentrazone-Ethyl	1	3	0
Cabbage	GoalTender	Oxyfluorfen	76	592	160
	Dacthal	Chlorthal-Dimethyl	65	495	1,494
	Arrow 2 EC	Clethodim	3	27	4
	Galigan 2E	Oxyfluorfen	3	20	5
	Goal 2XL	Oxyfluorfen	1	2	1
Cauliflower	GoalTender	Oxyfluorfen	401	4,192	1,172

Crop	Product	Active Ingredient	Fields	Acres	Lbs. AI
	Dacthal	Chlorthal-Dimethyl	210	2,061	5,797
	Prefar 4-E	Bensulide	18	175	437
	Galigan H2O	Oxyfluorfen	17	144	17
	Goal 2XL	Oxyfluorfen	12	162	14
	Galigan 2E	Oxyfluorfen	12	160	49
	Buccaneer	Glyphosate, Isopropylamine Salt	1	3	9
	ET	Pyraflufen-Ethyl	1	3	0
Chinese Cabbage	Dacthal	Chlorthal-Dimethyl	37	123	410
	Prefar 4-E	Bensulide	29	117	300
Kale	Prefar 4-E	Bensulide	126	950	3,518
	Dacthal	Chlorthal-Dimethyl	9	51	152
Kohlrabi	Dacthal	Chlorthal-Dimethyl	34	11	59
Leek	Dacthal	Chlorthal-Dimethyl	51	121	615
Lettuce, Head	Kerb SC	Propyzamide	1,651	18,831	11,348
	Prefar 4-E	Bensulide	547	6,069	16,711
	Shark EW	Carfentrazone-Ethyl	234	2,416	19
	K-Pam HL	Potassium N-Methyldithiocarbamate	49	1,257	323,741
	Balan	Benefin	31	252	139
	Roundup Powermax	Glyphosate, Potassium Salt	9	105	308
	Roundup Weathermax	Glyphosate, Potassium Salt	8	191	395
	Kerb 50-W	Propyzamide	2	27	19
	Dacthal	Chlorthal-Dimethyl	2	24	20
	Sequence	S-Metolachlor	1	12	1
		Glyphosate			0
	Rodeo	Glyphosate, Isopropylamine Salt	1	0	1
Onion (Not Green)	GoalTender	Oxyfluorfen	173	2,985	682
	Dacthal	Chlorthal-Dimethyl	121	2,235	13,341
	Maestro 4EC	Bromoxynil Octanoate	41	556	135
		Bromoxynil Heptanoate			130
	Prowl H2O	Pendimethalin	40	690	646
	Maestro 2EC	Bromoxynil Octanoate	37	609	303
	Outlook	Dimethenamid-P	36	655	408
	Galigan 2E	Oxyfluorfen	8	116	27
	Goal 2XL	Oxyfluorfen	7	71	16
	Roundup Powermax	Glyphosate, Potassium Salt	3	140	361
	ET	Pyraflufen-Ethyl	2	123	0

Crop	Product	Active Ingredient	Fields	Acres	Lbs. AI
	Prefar 4-E	Bensulide	2	51	146
	Nufarm Weedar 64	2,4-D, Dimethylamine Salt	1	24	10
	Gramoxone Sl	Paraquat Dichloride	1	17	24
	Buctril 4EC	Bromoxynil Octanoate	1	1	0
		Bromoxynil Heptanoate			0
Onions (Green)	Dacthal	Chlorthal-Dimethyl	16	87	438
Radish	Dacthal	Chlorthal-Dimethyl	30	49	226

Source: Authors' calculations derived from the CDPR Pesticide Use Reporting Database

Table 48. Herbicides Used on Fields in Monterey by Crop: 2016

Crop	Product	Active Ingredient	Fields	Acres	Lbs. AI
Bok Choy	Dacthal	Chlorthal-Dimethyl	45	75	231
	Prefar 4-E	Bensulide	18	55	220
	Kerb SC	Propyzamide	1	1	0
Broccoli	Dacthal	Chlorthal-Dimethyl	1,359	15,387	37,774
	GoalTender	Oxyfluorfen	925	10,297	2,934
	Prefar 4-E	Bensulide	440	4,276	11,965
	Devrinol 50-DF	Napropamide	106	1,122	642
	Goal 2XL	Oxyfluorfen	27	278	87
	Devrinol DF-XT	Napropamide	14	146	69
	Roundup Powermax	Glyphosate, Potassium Salt	12	121	413
	Trifluralin HF	Trifluralin	7	92	41
	Shark EW	Carfentrazone-Ethyl	6	73	1
	Galigan 2E	Oxyfluorfen	4	41	13
	Poast	Sethoxydim	3	51	13
	ET	Pyraflufen-Ethyl	3	50	0
	Arrow 2 EC	Clethodim	3	39	5
	Suppress	Caprylic Acid	3	8	171
		Capric Acid			117
	Gramoxone SL 2.0	Paraquat Dichloride	2	27	37
Brussels sprout	Dacthal	Chlorthal-Dimethyl	47	520	1,580
	Devrinol DF-XT	Napropamide	23	205	154
	Prefar 4-E	Bensulide	14	151	298
	Select Max	Clethodim	10	105	13
	Shark EW	Carfentrazone-Ethyl	5	156	5
	Devrinol 50-DF	Napropamide	4	48	36
	GoalTender	Oxyfluorfen	3	7	1
	Makaze	Glyphosate, Isopropylamine Salt	1	3	15
Cabbage	GoalTender	Oxyfluorfen	108	1,058	338
	Dacthal	Chlorthal-Dimethyl	87	648	1,856

Crop	Product	Active Ingredient	Fields	Acres	Lbs. AI
	Prefar 4-E	Bensulide	14	124	325
	Poast	Sethoxydim	10	76	20
	Goal 2XL	Oxyfluorfen	10	58	20
	Galigan 2E	Oxyfluorfen	3	37	9
	Makaze	Glyphosate, Isopropylamine Salt	2	40	120
	Goal 4F	Oxyfluorfen	1	12	3
Cauliflower	GoalTender	Oxyfluorfen	423	4,684	1,423
	dacthal	Chlorthal-Dimethyl	302	2,818	7,676
	Goal 2XL	Oxyfluorfen	26	234	28
	Prefar 4-E	Bensulide	24	236	528
	Devrinol 50-DF	Napropamide	6	36	26
	Endurance	Prodiamine	4	5	2
	Select Max	Clethodim	3	26	1
	Galigan 2E	Oxyfluorfen	2	25	6
	Devrinol DF-XT	Napropamide	2	20	15
	Goal Technical	Oxyfluorfen	1	1	1
	dacthal W-75	Chlorthal-Dimethyl	1	0	2
Chinese Cabbage	Dacthal	Chlorthal-Dimethyl	60	193	548
	Prefar 4-E	Bensulide	23	97	383
	Roundup Powermax	Glyphosate, Potassium Salt	1	4	4
	ET	Pyraflufen-Ethyl	1	4	0
Kale	Prefar 4-E	Bensulide	140	955	3,762
	Dacthal	Chlorthal-Dimethyl	52	266	1,223
Kohlrabi	Dacthal	Chlorthal-Dimethyl	34	21	113
Leek	Dacthal	Chlorthal-Dimethyl	83	226	1,455
	Satellite	Pendimethalin	44	133	119
	Roundup Powermax	Glyphosate, Potassium Salt	1	5	5
	ET	Pyraflufen-Ethyl	1	5	0
	Shark EW	Carfentrazone-Ethyl	1	1	0
Lettuce, Leaf	Kerb SC	Propyzamide	3,435	33,833	28,948
	Prefar 4-E	Bensulide	1,776	16,957	56,147
	Shark EW	Carfentrazone-Ethyl	304	2,249	27
	Balan	Benefin	138	1,584	1,009
	Roundup Powermax	Glyphosate, Potassium Salt	20	282	1,148
	ET	Pyraflufen-Ethyl	6	81	0
	Endurance	Prodiamine	5	4	2
	Arrow 2 EC	Clethodim	2	21	3
	Kerb 50-W	Propyzamide	2	0	0
	Caparol 4l	Prometryn	1	13	27

Crop	Product	Active Ingredient	Fields	Acres	Lbs. AI
	GoalTender	Oxyfluorfen	1	8	2
	Kerb SC T&O	Propyzamide	1	6	5
	Dacthal	Chlorthal-Dimethyl	1	5	4
	Prefar 6e	Bensulide	1	3	9
	Kerb 50-W	Propyzamide	1	0	0
	Weed Impede Concentrate	Glyphosate, Isopropylamine Salt	1	0	1
		Prodiamine			0
Mustard Greens	Prefar 4-E	Bensulide	51	258	1,006
	Dacthal	Chlorthal-Dimethyl	20	72	415
Onion (Not Green)	GoalTender	Oxyfluorfen	189	3,148	671
	Dacthal	Chlorthal-Dimethyl	116	2,011	12,032
	Outlook	Dimethenamid-P	46	812	449
	Maestro 4EC	Bromoxynil Octanoate	41	709	141
		Bromoxynil Heptanoate			136
	Prowl H2O	Pendimethalin	27	515	487
	Maestro 2EC	Bromoxynil Octanoate	20	330	168
	Galigan 2E	Oxyfluorfen	17	258	58
Onions (Green)	Dacthal	Chlorthal-Dimethyl	10	18	85
Radish	Dacthal	Chlorthal-Dimethyl	61	126	746

Source: Authors' calculations derived from the CDPR Pesticide Use Reporting Database

Table 49. Herbicides Used on Fields in San Luis Obispo by Crop: 2014

Crop	Product	Active Ingredient	Fields	Acres	Lbs. AI
Bok Choy	Dacthal	Chlorthal-Dimethyl	126	185	847
	Roundup Powermax	Glyphosate, Potassium Salt	4	6	10
Broccoli	GoalTender	Oxyfluorfen	911	8,191	2,557
	Devrinol DF-XT	Napropamide	114	1,096	954
	Trifluralin HF	Trifluralin	100	1,103	786
	Dacthal	Chlorthal-Dimethyl	37	252	934
	Triflurex	Trifluralin	23	526	283
	Goal 2XL	Oxyfluorfen	8	41	11
	Devrinol 50-DF	Napropamide	7	23	17
	Gramoxone SL 2.0	Paraquat Dichloride	5	38	52
	Arrow 2 EC	Clethodim	4	29	4
	Prefar 4-E	Bensulide	4	1	4
	Credit 41	Glyphosate, Isopropylamine Salt	3	19	77
	Makaze	Glyphosate, Isopropylamine Salt	2	22	43

Crop	Product	Active Ingredient	Fields	Acres	Lbs. AI
	Goal 4F	Oxyfluorfen	1	9	2
	Select Max	Clethodim	1	4	0
	Roundup Powermax	Glyphosate, Potassium Salt	1	0	1
	Honcho Plus	Glyphosate, Isopropylamine Salt	1	0	0
Brussels sprout	Dacthal	Chlorthal-Dimethyl	46	248	1,799
	Devrinol DF-XT	Napropamide	11	68	66
	ET	Pyraflufen-Ethyl	2	13	0
	Trifluralin HF	Trifluralin	1	6	0
Cabbage	GoalTender	Oxyfluorfen	98	432	130
	Dacthal	Chlorthal-Dimethyl	25	51	315
	Trifluralin HF	Trifluralin	7	20	15
	Prefar 4-E	Bensulide	3	0	2
	Goal 2XL	Oxyfluorfen	2	1	0
	Roundup Powermax	Glyphosate, Potassium Salt	1	7	10
	Gramoxone SL 2.0	Paraquat Dichloride	1	4	5
Cauliflower	GoalTender	Oxyfluorfen	200	1,889	528
	Devrinol DF-XT	Napropamide	49	410	403
	Trifluralin HF	Trifluralin	25	155	116
	Dacthal	Chlorthal-Dimethyl	24	198	770
	Makaze	Glyphosate, Isopropylamine Salt	8	74	37
	Goal 2XL	Oxyfluorfen	8	64	32
	Poast	Sethoxydim	2	13	3
	Goal 4F	Oxyfluorfen	1	8	3
	Trifluralin HF	Trifluralin	1	8	1
Chinese Cabbage	Dacthal	Chlorthal-Dimethyl	210	856	3,938
	ET	Pyraflufen-Ethyl	22	94	0
	Prefar 4-E	Bensulide	22	51	38
	Roundup Powermax	Glyphosate, Potassium Salt	10	36	62
	Gramoxone Sl	Paraquat Dichloride	2	12	17
	Prowl H2O	Pendimethalin	1	8	11
Kale	Dacthal	Chlorthal-Dimethyl	20	75	572
Leek	Dacthal	Chlorthal-Dimethyl	5	15	148
Mustard Greens	Dacthal	Chlorthal-Dimethyl	1	0	1
	Prefar 4-E	Bensulide	1	0	1
Onion (Not Green)	Outlook	Dimethenamid-P	18	130	8
	Dacthal	Chlorthal-Dimethyl	10	65	393

Crop	Product	Active Ingredient	Fields	Acres	Lbs. AI
	Prowl H2O	Pendimethalin	6	91	128
	Goal 2XL	Oxyfluorfen	6	91	23
	Maestro 4EC	Bromoxynil Octanoate	5	27	7
		Bromoxynil Heptanoate			7
	Intensity	Clethodim	4	73	19
	Fusilade Dx	Fluazifop-P-Butyl	2	14	3
	Intensity One	Clethodim	1	14	3
	Prefar 4-E	Bensulide	1	0	1
Nursery - Outdoor Grown Cut Flowers or Greens	98-2	Methyl Bromide	58	13	3,533
		Chloropicrin			72
	Terr 98	Methyl Bromide	21	13	2,699
	Dacthal	Chlorthal-Dimethyl	19	19	84
	Ronstar G	Oxadiazon	4	4	1
	Buccaneer	Glyphosate, Isopropylamine Salt	3	3	1
	Reglone	Diquat Dibromide	3	1	1
	Roundup Pro	Glyphosate, Isopropylamine Salt	2	1	4
	Gly Star Plus	Glyphosate, Isopropylamine Salt	1	1	0
	Oryzalin 4 A.S.	Oryzalin	1	1	0
	Ronstar 50 Wsp	Oxadiazon	1	0	0
	Goal 1.6e	Oxyfluorfen	1	0	0
Radish	Dacthal	Chlorthal-Dimethyl	2	1	7

Source: Authors' calculations derived from the CDPR Pesticide Use Reporting Database

Table 50. Herbicides Used on Fields in San Luis Obispo by Crop: 2015

Crop	Product	Active Ingredient	Fields	Acres	Lbs. AI
Bok Choy	Dacthal	Chlorthal-Dimethyl	144	220	1,091
	Roundup Powermax	Glyphosate, Potassium Salt	1	2	2
Broccoli	GoalTender	Oxyfluorfen	909	7,976	2,538
	Devrinol DF-XT	Napropamide	96	1,277	853
	Trifluralin HF	Trifluralin	73	1,084	581
	Devrinol 50-DF	Napropamide	6	53	40
	Goal 2XL	Oxyfluorfen	4	66	29
	Dacthal	Chlorthal-Dimethyl	3	5	26
	Triflurex	Trifluralin	2	49	20
	Roundup Powermax	Glyphosate, Potassium Salt	2	11	34
	Prefar 4-E	Bensulide	1	4	7
Brussels sprout	Dacthal	Chlorthal-Dimethyl	21	126	920
	Devrinol DF-XT	Napropamide	13	105	85
	Vapam Hl	Metam-Sodium	11	90	13,982

Crop	Product	Active Ingredient	Fields	Acres	Lbs. AI
	Prefar 4-E	Bensulide	6	44	256
	Devrinol 50-DF	Napropamide	1	4	4
Cabbage	GoalTender	Oxyfluorfen	121	623	189
	Dacthal	Chlorthal-Dimethyl	31	62	354
	Goal 2XL	Oxyfluorfen	4	27	8
	Trifluralin HF	Trifluralin	2	13	4
	Roundup Powermax	Glyphosate, Potassium Salt	2	5	10
	Gramoxone SL 2.0	Paraquat Dichloride	1	4	3
Cauliflower	GoalTender	Oxyfluorfen	309	2,753	803
	Devrinol DF-XT	Napropamide	21	175	171
	Vapam Hl	Metam-Sodium	13	137	30,136
	Trifluralin HF	Trifluralin	9	94	70
	Makaze	Glyphosate, Isopropylamine Salt	7	89	54
	Goal 2XL	Oxyfluorfen	5	17	9
	Dacthal	Chlorthal-Dimethyl	3	0	4
	Honcho Plus	Glyphosate, Isopropylamine Salt	1	0	0
Chinese Cabbage	Dacthal	Chlorthal-Dimethyl	152	627	3,907
	Prefar 4-E	Bensulide	11	25	66
	ET	Pyraflufen-Ethyl	9	59	0
	Roundup Powermax	Glyphosate, Potassium Salt	4	13	30
	Gramoxone SL 2.0	Paraquat Dichloride	2	4	6
Kale	Dacthal	Chlorthal-Dimethyl	18	48	353
	Shark EW	Carfentrazone-Ethyl	17	64	1
	Axxe	Ammonium Nonanoate	2	40	801
	Roundup Powermax	Glyphosate, Potassium Salt	2	10	16
Kohlrabi	Dacthal	Chlorthal-Dimethyl	1	0	1
	Goal 2XL	Oxyfluorfen	1	0	0
Leek	Dacthal	Chlorthal-Dimethyl	16	32	169
	Roundup Powermax	Glyphosate, Potassium Salt	1	2	6
Onions (Green)	Dacthal	Chlorthal-Dimethyl	1	0	3
	Roundup Powermax	Glyphosate, Potassium Salt	1	0	0
Radish	Dacthal	Chlorthal-Dimethyl	3	1	11

Source: Authors' calculations derived from the CDPR Pesticide Use Reporting Database

Table 51. Herbicides Used on Fields in San Luis Obispo by Crop: 2016

Crop	**Product**	**Active Ingredient**	**Fields**	**Acres**	**Lbs. AI**
Bok Choy	Dacthal	Chlorthal-Dimethyl	120	189	765
	Gramoxone SL 2.0	Paraquat Dichloride	2	5	6
	Roundup Powermax	Glyphosate, Potassium Salt	1	2	6
Broccoli	GoalTender	Oxyfluorfen	634	5,834	1,823
	Devrinol DF-XT	Napropamide	70	1,013	746
	Trifluralin HF	Trifluralin	67	1,020	643
	Goal 2XL	Oxyfluorfen	19	371	160
	Gramoxone SL 2.0	Paraquat Dichloride	4	14	19
	Devrinol 2-Xt	Napropamide	3	34	23
	Makaze	Glyphosate, Isopropylamine Salt	2	25	15
	Devrinol DF-XT	Napropamide	1	14	7
	Dacthal	Chlorthal-Dimethyl	1	2	9
	Roundup Powermax	Glyphosate, Potassium Salt	1	1	2
Brussels sprout	Dacthal	Chlorthal-Dimethyl	77	531	2,787
	Devrinol DF-XT	Napropamide	59	430	423
	Vapam Hl	Metam-Sodium	20	173	11,552
	Makaze	Glyphosate, Isopropylamine Salt	18	142	193
	Prefar 4-E	Bensulide	18	137	815
	Devrinol 50-DF	Napropamide	13	54	30
	Shark EW	Carfentrazone-Ethyl	5	56	1
Cabbage	GoalTender	Oxyfluorfen	97	442	151
	Dacthal	Chlorthal-Dimethyl	2	6	23
	Gramoxone SL 2.0	Paraquat Dichloride	1	7	10
Chinese Cabbage	Dacthal	Chlorthal-Dimethyl	141	633	3,523
	Prefar 4-E	Bensulide	14	32	54
	Roundup Powermax	Glyphosate, Potassium Salt	6	17	46
	Gramoxone SL 2.0	Paraquat Dichloride	3	11	14
	ET	Pyraflufen-Ethyl	1	6	0
Kale	Dacthal	Chlorthal-Dimethyl	16	27	138
	Mon 65005	Glyphosate, Isopropylamine Salt	2	1	0
	Roundup Powermax	Glyphosate, Potassium Salt	1	2	6
Leek	Dacthal	Chlorthal-Dimethyl	5	17	91
	Roundup Powermax	Glyphosate, Potassium Salt	1	1	3

Crop	Product	Active Ingredient	Fields	Acres	Lbs. AI
Onions (Green)	Dacthal	Chlorthal-Dimethyl	1	1	4
Radish	Dacthal	Chlorthal-Dimethyl	1	0	2
Tomato	Dacthal	Chlorthal-Dimethyl	1	3	18
	Makaze	Glyphosate, Isopropylamine Salt	1	3	2

Source: Authors' calculations derived from the CDPR Pesticide Use Reporting Database

Table 52. Herbicides Used on Fields in Santa Barbara by Crop: 2014

Crop	Product	Active Ingredient	Fields	Acres Treated	Lbs. AI
Bok Choy	Dacthal	Chlorthal-Dimethyl	36	87	276
Broccoli	GoalTender	Oxyfluorfen	2,346	24,953	7,567
	Devrinol DF-XT	Napropamide	388	4,557	3,590
	Trifluralin HF	Trifluralin	320	3,803	2,340
	Goal 2XL	Oxyfluorfen	149	2,034	890
	Dacthal	Chlorthal-Dimethyl	45	550	2,030
	Goal 2XL Herbicide	Oxyfluorfen	19	369	72
	Devrinol 50-DF	Napropamide	19	197	148
	Triflurex	Trifluralin	17	106	83
	ET	Pyraflufen-Ethyl	5	61	0
	Prefar 4-E	Bensulide	5	48	141
	Shark EW	Carfentrazone-Ethyl	4	18	0
	Credit 41	Glyphosate, Isopropylamine Salt	3	33	131
	Roundup Powermax	Glyphosate, Potassium Salt	3	33	90
	Gly Star Plus	Glyphosate, Isopropylamine Salt	3	30	90
	Poast	Sethoxydim	3	27	7
	Vegetable Pro	Prometryn	2	2	2
	Select Max	Clethodim	1	15	2
	Gramoxone SL 2.0	Paraquat Dichloride	1	12	2
	Honcho Plus	Glyphosate, Isopropylamine Salt	1	9	14
	Honcho	Glyphosate, Isopropylamine Salt	1	2	1
Brussels Sprout	Devrinol DF-XT	Napropamide	23	355	207
	Dacthal	Chlorthal-Dimethyl	21	341	1,559
	Prefar 4-E	Bensulide	7	37	217

Crop	Product	Active Ingredient	Fields	Acres Treated	Lbs. AI
Cauliflower	GoalTender	Oxyfluorfen	780	8,101	2,261
	Devrinol DF-XT	Napropamide	117	1,167	1,098
	Goal 2XL	Oxyfluorfen	99	1,079	511
	Trifluralin HF	Trifluralin	95	980	730
	Dacthal	Chlorthal-Dimethyl	11	114	510
	Devrinol 50-DF	Napropamide	11	91	68
	ET	Pyraflufen-Ethyl	5	71	0
	Roundup Powermax	Glyphosate, Potassium Salt	5	51	152
	Makaze	Glyphosate, Isopropylamine Salt	5	47	23
	Gly Star Plus	Glyphosate, Isopropylamine Salt	2	31	23
	Poast	Sethoxydim	2	13	3
	Ro-Neet 6-E	Cycloate	2	8	9
	Shark EW	Carfentrazone-Ethyl	1	12	0
	Honcho	Glyphosate, Isopropylamine Salt	1	2	1
Chinese Cabbage	Dacthal	Chlorthal-Dimethyl	36	206	670
	Dacthal W-75	Chlorthal-Dimethyl	2	8	54
	GoalTender	Oxyfluorfen	1	9	3
Collards	Dacthal	Chlorthal-Dimethyl	3	12	61
	Triflurex	Trifluralin	2	6	3
Kale	Dacthal	Chlorthal-Dimethyl	17	50	183
	Prefar 4-E	Bensulide	8	32	113
	Triflurex	Trifluralin	4	15	8
Kohlrabi	Dacthal	Chlorthal-Dimethyl	43	50	229
Mustard Greens	Dacthal	Chlorthal-Dimethyl	11	18	105
	Triflurex	Trifluralin	11	18	10
Nursery - Outdoor Container/Field	Kleenup Pro	Glyphosate, Isopropylamine Salt	163	249	1,209
	Reward Landscape	Diquat Dibromide	162	247	151
	Honcho Plus	Glyphosate, Isopropylamine Salt	32	295	729
	Prowl H2O	Pendimethalin	18	5,759	2,045
	Dupont Matrix SG	Rimsulfuron	18	5,759	13
	Reward Aquatic	Diquat Dibromide	10	10	5
	Cleary's MCPP	MCPP, Potassium Salt	9	21	4
	Nufarm Diquat SPC	Diquat Dibromide	8	69	94

Crop	Product	Active Ingredient	Fields	Acres Treated	Lbs. AI
	Pendulum 2G	Pendimethalin	7	119	8
	Dacthal	Chlorthal-Dimethyl	7	47	485
	Mon 52249	Glyphosate, Isopropylamine Salt	6	10	5
	Snapshot 2.5 TG	Trifluralin	5	20	30
		Isoxaben			8
	Roundup Promax	Glyphosate, Potassium Salt	5	5	0
	Roundup Original Max	Glyphosate, Potassium Salt	4	1,268	17
	Reglone	Diquat Dibromide	4	1,097	12
	Roundup Powermax	Glyphosate, Potassium Salt	2	622	17
	Roundup Weathermax	Glyphosate, Potassium Salt	2	6	12
	Trifluralin HF	Trifluralin	1	376	131
	Quali-Pro Oxadiazon	Oxadiazon	1	17	6
	Pendulum Granule	Pendimethalin	1	17	1
	Roundup Pro	Glyphosate, Isopropylamine Salt	1	2	4
	Diquat Herbicide	Diquat Dibromide	1	1	0
	Remuda Full	Glyphosate, Isopropylamine Salt	1	1	1
Nursery - Outdoor Grown Cut Flowers or Greens	Pennant Magnum	S-Metolachlor	160	814	1,300
	Reward Aquatic	Diquat Dibromide	115	650	646
	Dacthal	Chlorthal-Dimethyl	93	467	2,395
	Ranger Pro	Glyphosate, Isopropylamine Salt	33	192	1,805
	Surflan AS	Oryzalin	30	91	353
	K-Pam HL	Potassium N-Methyldithiocarbamate	17	198	26,061
	Fusilade II	Fluazifop-P-Butyl	17	109	55
	Rubigan AS	Fenarimol	16	67	3
	Brom 2%	Methyl Bromide	10	2	454
	Accord SP	Glyphosate, Isopropylamine Salt	8	23	257
	Roundup Powermax	Glyphosate, Potassium Salt	5	36	100
	ET	Pyraflufen-Ethyl	5	36	0
	Dual 25G	Metolachlor	1	6	1
	Dual Magnum	S-Metolachlor	1	3	6
	Grim Reaper	Petroleum Oil, Unclassified	1	3	2
		2,4-D, Isooctyl Ester			0
		Pentachlorophenol			0
		Bromacil			0
		PCP, Other Related			0

Crop	Product	Active Ingredient	Fields	Acres Treated	Lbs. AI
	Roundup Pro	Glyphosate, Isopropylamine Salt	1	2	4
Radish	Dacthal	Chlorthal-Dimethyl	1	1	8

Source: Authors' calculations derived from the CDPR Pesticide Use Reporting Database

Table 53. Herbicides Used on Fields in Santa Barbara by Crop: 2015

Crop	Product	Active Ingredient	Fields	Acres Treated	Lbs. AI
Bok Choy	Dacthal	Chlorthal-Dimethyl	91	247	774
	Prefar 4-E	Bensulide	32	20	66
Broccoli	GoalTender	Oxyfluorfen	2,157	22,219	6,672
	Trifluralin HF	Trifluralin	442	5,088	2,737
	Devrinol DF-XT	Napropamide	279	3,213	2,324
	Goal 2XL	Oxyfluorfen	191	2,401	976
	Triflurex	Trifluralin	39	403	231
	Dacthal	Chlorthal-Dimethyl	15	230	840
	Makaze	Glyphosate, Isopropylamine Salt	11	140	375
	Poast	Sethoxydim	6	84	22
	Devrinol 50-DF	Napropamide	2	17	9
	Goal 4F	Oxyfluorfen	1	12	2
	Kerb SC	Propyzamide	1	7	7
	Gramoxone	Paraquat Dichloride	1	6	6
	Shark EW	Carfentrazone-Ethyl	1	4	0
Brussels Sprout	Prefar 4-E	Bensulide	21	294	1,212
	Devrinol DF-XT	Napropamide	20	295	279
	Dacthal	Chlorthal-Dimethyl	15	126	643
	Devrinol 50-DF	Napropamide	6	62	39
	Select Max	Clethodim	2	11	1
	Roundup Powermax	Glyphosate, Potassium Salt	1	4	11
	ET	Pyraflufen-Ethyl	1	4	0
Cauliflower	GoalTender	Oxyfluorfen	949	9,585	2,588
	Goal 2XL	Oxyfluorfen	151	1,791	812
	Trifluralin HF	Trifluralin	117	1,175	684
	Devrinol DF-XT	Napropamide	58	516	425
	Dacthal	Chlorthal-Dimethyl	12	113	532
	Triflurex	Trifluralin	11	129	62

Crop	Product	Active Ingredient	Fields	Acres Treated	Lbs. AI
	Makaze	Glyphosate, Isopropylamine Salt	4	29	14
	Goal 4F	Oxyfluorfen	2	14	3
	Devrinol 50-DF	Napropamide	1	6	5
	Shark EW	Carfentrazone-Ethyl	1	6	0
Chinese Cabbage	Dacthal	Chlorthal-Dimethyl	92	502	1,815
Collards	Dacthal	Chlorthal-Dimethyl	2	5	25
	Triflurex	Trifluralin	2	5	3
Kale	Dacthal	Chlorthal-Dimethyl	68	114	492
	Prefar 4-E	Bensulide	65	100	134
	Triflurex	Trifluralin	3	9	5
Kohlrabi	Dacthal	Chlorthal-Dimethyl	48	658	2,978
	Prefar 4-E	Bensulide	42	652	646
Leek	Dacthal	Chlorthal-Dimethyl	3	7	59
Mustard Greens	Dacthal	Chlorthal-Dimethyl	6	15	79
	Triflurex	Trifluralin	6	15	8
Onion (Not Green)	Goal 2XL	Oxyfluorfen	24	2,336	141
	Outlook	Dimethenamid-P	12	1,168	575
	Prowl H2O	Pendimethalin	7	461	202
	Maestro 4EC	Bromoxynil Octanoate	7	461	35
		Bromoxynil Heptanoate			34
	Buctril 4EC	Bromoxynil Octanoate	6	584	54
		Bromoxynil Heptanoate			52
	Cleanse 2 EC	Clethodim	4	194	51
	Arrow 2 EC	Clethodim	2	390	104
	Dacthal	Chlorthal-Dimethyl	1	1	3
	GoalTender	Oxyfluorfen	1	1	0
Nursery - Outdoor Container/Field	Reward Landscape	Diquat Dibromide	108	171	89
	Ranger Pro	Glyphosate, Isopropylamine Salt	66	111	522
	Kleenup Pro	Glyphosate, Isopropylamine Salt	44	67	306
	Honcho Plus	Glyphosate, Isopropylamine Salt	41	400	783
	Reward Aquatic	Diquat Dibromide	17	17	8

Crop	Product	Active Ingredient	Fields	Acres Treated	Lbs. AI
	Dacthal	Chlorthal-Dimethyl	16	130	1,286
	Pendulum 2G	Pendimethalin	7	103	6
	Nufarm Diquat SPC	Diquat Dibromide	7	56	66
	Roundup Pro	Glyphosate, Isopropylamine Salt	6	17	37
	Roundup Promax	Glyphosate, Potassium Salt	6	6	0
	Roundup Powermax	Glyphosate, Potassium Salt	4	1,130	18
	Prefar 4-E	Bensulide	4	36	143
	Cleary's MCPP	MCPP, Potassium Salt	4	9	1
	Quali-Pro Oxadiazon	Oxadiazon	3	51	9
	Satellite	Pendimethalin	2	752	1,103
	Trellis	Isoxaben	2	752	231
	Reglone	Diquat Dibromide	2	752	144
	Reward	Diquat Dibromide	2	2	22
	Mbc Concentrate	Methyl Bromide	1	20	5,866
	Diquat Herbicide	Diquat Dibromide	1	8	9
	Snapshot 2.5 TG	Trifluralin	1	5	8
		Isoxaben			2
	Remuda Full	Glyphosate, Isopropylamine Salt	1	1	2
Nursery - Outdoor Grown Cut Flowers or Greens	Pennant Magnum	S-Metolachlor	122	754	1,144
	Dacthal	Chlorthal-Dimethyl	109	580	2,842
	Reward Aquatic	Diquat Dibromide	89	512	880
	K-Pam HL	Potassium N-Methyldithiocarbamate	28	487	71,741
	Accord SP	Glyphosate, Isopropylamine Salt	21	132	1,571
	Ranger Pro	Glyphosate, Isopropylamine Salt	8	70	427
	Pendulum Aquacap	Pendimethalin	8	69	272
	Fusilade II	Fluazifop-P-Butyl	7	29	15
	Kleenup Pro	Glyphosate, Isopropylamine Salt	7	1	2
	Reward Landscape	Diquat Dibromide	7	1	0
	Terr 98	Methyl Bromide	6	2	297
	Honcho	Glyphosate, Isopropylamine Salt	4	0	1

Crop	Product	Active Ingredient	Fields	Acres Treated	Lbs. AI
	Roundup Pro	Glyphosate, Isopropylamine Salt	3	8	15
	Quali-Pro Oxadiazon	Oxadiazon	3	0	1
	Rubigan AS	Fenarimol	2	10	0
	Roundup Powermax	Glyphosate, Potassium Salt	1	8	23
	Ronstar G	Oxadiazon	1	4	6
	Sedgehammer	Halosulfuron-Methyl	1	0	0
Radish	Dacthal	Chlorthal-Dimethyl	1	1	8

Source: Authors' calculations derived from the CDPR Pesticide Use Reporting Database

Table 54. Herbicides Used on Fields in Santa Barbara by Crop: 2016

Crop	Product	Active Ingredient	Fields	Acre Treated	Lbs. AI
Bok Choy	Dacthal	Chlorthal-Dimethyl	151	302	939
	Prefar 4-E	Bensulide	38	38	31
	Goal 2XL	Oxyfluorfen	2	17	4
Broccoli	GoalTender	Oxyfluorfen	1,913	19,078	5,870
	Trifluralin HF	Trifluralin	324	3,511	2,063
	Devrinol DF-XT	Napropamide	173	2,119	1,796
	Goal 2XL	Oxyfluorfen	151	1,794	717
	Triflurex	Trifluralin	39	385	271
	Dacthal	Chlorthal-Dimethyl	13	74	348
	Makaze	Glyphosate, Isopropylamine Salt	11	156	391
	Devrinol 2-Xt	Napropamide	8	111	101
	Roundup Powermax	Glyphosate, Potassium Salt	8	106	297
	Goal 2XL Herbicide	Oxyfluorfen	8	101	29
	ET	Pyraflufen-Ethyl	5	48	0
	Honcho Plus	Glyphosate, Isopropylamine Salt	4	24	60
	Alecto 41-S	Glyphosate, Isopropylamine Salt	4	22	66
	Shark EW	Carfentrazone-Ethyl	3	89	3
	Poast	Sethoxydim	3	24	5
	Arrow 2 EC	Clethodim	3	21	3
	Vapam Hl	Metam-Sodium	3	21	2,083
	Trifluralin 10g	Trifluralin	2	25	4
	Devrinol 50-DF	Napropamide	2	15	15
	Trifluralin HF	Trifluralin	2	14	8
	Devrinol 50-DF	Napropamide	1	26	20
	Prefar 4-E	Bensulide	1	10	10
	Poast	Sethoxydim	1	9	2

	Select Max	Clethodim	1	9	1
	Suppress	Caprylic Acid	1	5	79
		Capric Acid			54
Brussels Sprout	Dacthal	Chlorthal-Dimethyl	64	812	3,616
	Devrinol 50-DF	Napropamide	49	689	344
	Prefar 4-E	Bensulide	8	67	354
	Devrinol DF-XT	Napropamide	5	46	28
Cauliflower	GoalTender	Oxyfluorfen	966	9,454	2,658
	Goal 2XL	Oxyfluorfen	179	1,852	862
	Trifluralin HF	Trifluralin	104	995	660
	Devrinol DF-XT	Napropamide	90	941	867
	Triflurex	Trifluralin	41	352	193
	Goal 2XL Herbicide	Oxyfluorfen	19	194	69
	Devrinol 50-DF	Napropamide	5	49	37
	Makaze	Glyphosate, Isopropylamine Salt	3	24	18
	Trifluralin HF	Trifluralin	3	21	16
	Roundup Powermax	Glyphosate, Potassium Salt	2	27	82
	Shark EW	Carfentrazone-Ethyl	2	27	1
	Devrinol 2-Xt	Napropamide	2	14	13
	Kerb SC	Propyzamide	1	10	17
	Dacthal	Chlorthal-Dimethyl	1	4	18
Chinese Cabbage	Dacthal	Chlorthal-Dimethyl	91	367	1,306
Kale	Dacthal	Chlorthal-Dimethyl	55	139	592
	Prefar 4-E	Bensulide	40	115	146
	Select Max	Clethodim	1	4	0
Kohlrabi	Dacthal	Chlorthal-Dimethyl	46	57	258
	Prefar 4-E	Bensulide	46	57	56
Leek	Dacthal	Chlorthal-Dimethyl	7	21	112
Nursery - Outdoor Container/Field	Reward Landscape	Diquat Dibromide	124	135	81
	Kleenup Pro	Glyphosate, Isopropylamine Salt	119	124	468
	Dacthal	Chlorthal-Dimethyl	22	189	1,627
	Prefar 4-E	Bensulide	20	168	666
	Nufarm Diquat SPC	Diquat Dibromide	19	119	103
	Ranger Pro	Glyphosate, Isopropylamine Salt	17	28	100
	Honcho Plus	Glyphosate, Isopropylamine Salt	15	268	737
	Reward Aquatic	Diquat Dibromide	7	7	3
	Pendulum 2G	Pendimethalin	6	93	5
	Roundup Pro	Glyphosate, Isopropylamine Salt	6	16	31
	Diquat Herbicide	Diquat Dibromide	4	379	11
	Quali-Pro Oxadiazon	Oxadiazon	3	51	8

	Roundup Promax	Glyphosate, Potassium Salt	3	3	0
	Fugitive	Oryzalin	2	752	252
	Satellite	Pendimethalin	2	752	226
	Roundup Powermax	Glyphosate, Potassium Salt	2	752	107
	Remuda Full	Glyphosate, Isopropylamine Salt	2	2	3
	Trifluralin HF	Trifluralin	1	376	42
	Trellis	Isoxaben	1	376	6
	Dupont Matrix SG	Rimsulfuron	1	376	2
	Treevix	Saflufenacil	1	376	0
	Shark EW	Carfentrazone-Ethyl	1	376	0
	Mbc Concentrate	Methyl Bromide	1	20	6,000
Nursery - Outdoor Grown Cut Flowers or Greens	Pennant Magnum	S-Metolachlor	102	639	977
	Reward Aquatic	Diquat Dibromide	79	535	1,011
	Dacthal	Chlorthal-Dimethyl	78	498	2,363
	Ranger Pro	Glyphosate, Isopropylamine Salt	25	199	2,003
	K-Pam HL	Potassium N-Methyldithiocarbamate	18	268	44,448
	Fusilade II	Fluazifop-P-Butyl	14	103	52
	Kleenup Pro	Glyphosate, Isopropylamine Salt	10	108	432
	Reward Landscape	Diquat Dibromide	7	44	41
	Lorox Df	Linuron	5	62	62
	Terr 98	Methyl Bromide	3	1	110
	Quali-Pro Oxadiazon	Oxadiazon	3	0	1
	Prefar 4-E	Bensulide	2	16	63
	Accord SP	Glyphosate, Isopropylamine Salt	2	15	153
	Roundup Pro	Glyphosate, Isopropylamine Salt	2	4	8
	Honcho Plus	Glyphosate, Isopropylamine Salt	1	3	0
	Nufarm Diquat SPC	Diquat Dibromide	1	2	1
Tomato	Dacthal	Chlorthal-Dimethyl	1	2	12
	Makaze	Glyphosate, Isopropylamine Salt	1	2	4
Turnip	Dacthal	Chlorthal-Dimethyl	20	31	93

Source: Authors' calculations derived from the CDPR Pesticide Use Reporting Database

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BIOGRAPHICAL SKETCH

NAME:	POSITION TITLE:
Steven A. Fennimore	Cooperative Extension Specialist

EDUCATION/TRAINING

INSTITUTION AND LOCATION	DEGREE	YEAR(s)	FIELD OF STUDY
University of Oregon	B.A.	1977	Public Affairs
University of California, Davis	M.Sc.	1983	Weed Science
Purdue University	Ph.D.	1997	Weed Science

EMPLOYMENT HISTORY

1997 to present, University of California, Davis.
Extension Specialist and Weed Ecophysiologist, Department of Plant Sciences, July 2009 to present.
Associate Extension Specialist and Weed Ecophysiologist, Department of Plant Sciences, July 2003 to June 2009.
Assistant Extension Specialist and Weed Ecophysiologist, Department of Vegetable Crops, Sept. 1997 to June 2003.
1994 to 1997, Purdue University.
Graduate Research Assistant and Purdue Research Fellow, Department of Botany and Plant Pathology.
1983 to 1994, Zeneca Agricultural Products (Previously ICI Agricultural Products).
Field Development Representative, Lafayette, IN 1988 -1994.
Assistant Plant Physiologist, Visalia, CA 1983-1987.
1977 to 1979, Peace Corps Volunteer, Paraguay

PROFESSIONAL ACTIVITIES

1. American Society for Horticultural Science.
2. California Weed Science Society.
3. Weed Science Society of America.
4. Methyl Bromide Alternatives Outreach.
5. European Weed Research Society – Physical and Cultural Weed Control Workgroup

HONORS AND AWARDS

1. Purdue Research Foundation Fellowship, 1995 – 1997
2. Phi Kappa Phi, 1997
3. DowElanco Graduate Scholarship, 1997
4. Dupont Graduate Scholarship, 1997
5. California Weed Science Society Award of Excellence, 2001
6. California Weed Science Society President, 2013
7. Oscar Lorenz Award, 2015
8. California Weed Science Society Award of Excellence, 2016
9. California Weed Science Society Honorary Member, 2019
10. Fulbright Scholar, Uruguay, 2019
11. EurAgEng Outstanding Paper Award 2020

GRANTS RECEIVED

1. USDA NIFA Methyl Bromide Transitions. Integration of allyl-isothiocyanate, steam & exothermic substances for soil disinfestation in strawberry nurseries. $499,749
2. USDA NIFA Crop protection & pest management. Band Steam Application for Weed and Disease Control in Vegetable Crops . $174,126
3. USDA NIFA Methyl Bromide Transitions. Site-specific soil pest management using crop rotation and a needs-based variable rate fumigation strategy. 2019-2022. S. Fennimore and F. Martin. This work is focused on precision mapping of soil pathogens and precision application of fumigants. $156,110

BIOGRAPHICAL SKETCH

NAME:	POSITION TITLE:
Steven A. Fennimore	Cooperative Extension Specialist

PUBLICATIONS since 2017

1. Xu Y., R.E.Goodhue, J.A. Chalfant, T. Miller and S.A. Fennimore. 2017. Economic viability of steam as an alternative to preplant soil fumigation in California strawberry production. 2017. HortScience 52:401-407.
2. Hoffmann, M., A. Barbella, T. Miller, J. Broome, F. Martin, S. Koike, J. Rachuy, I. Greene, N. Dorn, R. Goodhue, and S. Fennimore. 2017. Weed and pathogen control with steam in California strawberry production. Acta Hort. 1156: 593-601.
3. Hoffmann, M., S.A. Fennimore. 2017. A Soil Probe System to Evaluate Weed Seed Survival in Soil Disinfestation Trials. Weed Technology. 31:752-760. DOI: 10.1017/wet.2017.36
4. Dr. Carol Shennan, Dr. Joji Muramoto, Dr. Steven T. Koike, Mr. Graeme Baird, Dr. Steven Fennimore, Dr. Jayesh Samtani, Mr Mark Bolda, Dr. Surendra Dara, Dr. Oleg Daugovish, Dr. George Lazarovits, Dr. David Butler, Dr. Erin Rosskopf, Dr. Nancy Kokalis-Burelle, Karen Klonsky, Mark Mazzola 2018. Anaerobic soil disinfestation is an alternative to soil fumigation for control of some soilborne pathogens in strawberry production. Plant Pathology. DOI: 10.1111/ppa.12721 Plant Pathology 67:51-66.
5. Westwood JH, Charudattan R, Duke SO, Fennimore SA, Marrone P, Slaughter DC, Swanton C, Zollinger R (2018) Weed Management in 2050: Perspectives on the Future of Weed Science. Weed Science 66:275-285
6. Fennimore SA, NS Boyd. Sustainable Weed Control in Strawberry. Chapter 20 pp. 383-403 (in press) In Korres, N.E., Burgos, N.R. and S.O. Duke (eds.) Weed Control: Sustainability, Hazards and Risks in Cropping Systems Worldwide. Science Publishers, CRS Press / Taylor & Francis Group.
7. Samtani JB, Rom CR, Friedrich H, Fennimore SA, Finn CE, Petran A, Wallace RW, Pritts MP, Fernandez G, Chase C, Kubota C and Bergefurd B. 2019. The Status and Future of the Strawberry Industry in the United States. HortTech doi.org/10.21273/HORTTECH04135-18
8. Fennimore SA, Cutulle M. 2019. Robotic weeders can improve weed control options for specialty crops. Pest Management Sci. https://doi.org/10.1002/ps.5337
9. Hoffmann M, Ajwa HA, Westerdahl BB, Koike ST, Stanghellini M, Wilen C, Fennimore SA 2020. Multi-tactic pre-plant soil fumigation with allyl isothiocyanate in cut-flower and strawberry. HORTTECH 30:251-258.
10. Fennimore S, Tourte L (2019) Regulatory Burdens on Development of Automated Weeding Machines and Herbicides Are Different. Outlooks on Pest Management 30(4):147-152.
11. Su WH, Fennimore SA, Slaughter DC. (2019) Fluorescence imaging for rapid monitoring of translocation behavior of systemic markers in snap beans for automated crop/weed discrimination. Biosystems Engineering 186: 156–167.
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14. Kim S, Kim DS, Fennimore SA Incorporating statistical strategy into image analysis to estimate effects of steam and allyl isocyanate on weed control PLOS One https://doi.org/10.1371/journal.pone.0222695
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17. Raja R, Nguyen TT, Slaughter DC, Fennimore SA (2020) Real-time weed-crop classification and localization technique for robotic weed control in lettuce. Biosystems Engineering. 192:257-274.
18. Rachuy JS and Fennimore SA (2021) Vegetable response to sulfentrazone soil residues at four planting intervals. Weed Technol. 35: 216–222. doi: 10.1017/wet.2020.100

BIOGRAPHICAL SKETCH

NAME:	**POSITION TITLE:**
Steven A. Fennimore	Cooperative Extension Specialist

19. Michuda A, Goodhue RE, Hoffmann M and Fennimore SA. (2021) Predicting Net Returns of Organic and Conventional Strawberry Following Soil Disinfestation with Steam or Steam Plus Additives. *Agronomy* **2021**, *11*, 149. https://doi.org/10.3390/agronomy11010149

20. Kim DS, Kim S, Fennimore S. (2021) Evaluation of Broadcast Steam Application with Mustard Seed Meal in Fruiting Strawberry. HORTSCIENCE 56(4):500–505. https://doi.org/10.21273/HORTSCI15669-20

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EDUCATION
Master of Science, Agronomy, 1985, U.C. Davis
Bachelor of Arts, Biology, 1977, Sonoma State University

EXPERIENCE
1985-present University of California, Cooperative Extension
1981-1985 University of California, Davis, Dept of Agronomy

CURRENT POSITION
Farm Advisor, Vegetable Crops and Weed Science, University of California Cooperative Extension Monterey County

Responsible for conducting a research and education program in vegetable crop production and weed science. Crops include cool season vegetables such as lettuce, cole crops, celery, onions and spinach as well as warm season crops such as peppers, squash. Establish research and educational programs to meet the needs of growers and the allied agricultural industry. Conduct research on cultural practices, weed science, soil fertility and new crop development. Primary area of expertise includes weed science, soil fertility and plant nutrition. Conduct educational programs through newsletters, field days, meetings and farm calls. December, 1985 to present.

PROFESSIONAL ORGANIZATIONS
American Society for Horticultural Science
California Chapter of the American Society of Agronomy
Weed Science Society

AWARDS AND HONORS
2016 ASHS Extension Publication Award – Most outstanding publication on horticultural extension 2016
2008 Western Extension Directors Association Award of Excellence (Farm Water Quality Project team member)
2004 California Weed Science Society Award of Excellence
2003 Oscar Lorenz Award – Dept of Plant Science, UCD

SELECTED PUBLICATIONS

Miller K., B.J. Aegerter, N. E. Clark, M. Leinfelder-Miles, E. M. Miyao, R.F. Smith, R. Wilson and D. Geisseler. 2018. Relationship between soil properties and nitrogen mineralization in undisturbed soil cores from California agroecosystems. Communications in Plant and Soil Analysis: November, https://doi.org/10.1080/00103624.2018.1554668

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Lati, R.N., Mou, B.Q., Rachuy, J.S., R.F. Smith, S.K. Dara, O. Daugovish and S.K. Fennimore. 2015. Weed management in transplanted lettuce with Pendimethalin and S-metolachlor. Weed Technology: 29:827-834.

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