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PATTERNS OF PESTICIDE USE IN CALIFORNIA AND THE IMPLICATIONS FOR STRATEGIES FOR REDUCTION OF PESTICIDES

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■ **Abstract** We used the California Pesticide Use Reports to study use of fungicides, bactericides, fumigants, and selected insecticides, primarily for vegetable, fruit, and nut production in California from 1993 to 2000. There were no obvious trends in decreased use of most compounds used to treat plant disease. However, growers have rapidly adopted recently introduced “conventional” compounds. There is very limited use of microbial biocontrol agents to control plant disease and no indication of an increase. We used case studies to explore the potential of different strategies to reduce pesticide use or risk. There have been reductions in use of organophosphate insecticides, largely by substitution with pyrethroids. Theoretically, replacement of “calendar spray” pesticide programs with “environmentally driven” programs could reduce pesticide use in years with lower disease pressure, but this assumes that the majority of growers currently use a “calendar spray” program and that growers who use less than recommended by an environmentally driven program would not increase their use.

INTRODUCTION

The unifying goal of plant pathology is to control plant disease, and chemicals play a major role in accomplishing that goal in contemporary agricultural production (10, 28, 65). In response to social pressure about adverse effects of pesticides, there is much public and regulatory discussion about reduction of pesticide use. Data from the California Pesticide Use Reports (PUR) support the hypothesis that relatively little reduction occurred during the decade of the 1990s, even though there is nationwide infrastructure in the land grant universities, Cooperative Extension Service, and USDA that presumably have a goal of reduction of pesticide use or risk. Consequently, we present selected case studies on agricultural pesticide use in California to explore the potential effectiveness of different strategies for reduction of pesticide use or risk. Finally, we discuss possible reasons why greater changes in pesticide use have not occurred.

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USE OF FUNGICIDES, BACTERICIDES, AND FUMIGANTS FOR VEGETABLE, FRUIT, AND NUT PRODUCTION IN CALIFORNIA FROM 1993 TO 2000

Introduction to Agricultural Pesticide Use in the United States and in California

The global crop protection market has gross annual sales valued at approximately $31 billion, with approximately 25% of sales in the United States (69). A survey by the American Crop Protection Association reported that herbicides, insecticides, and fungicides account for 68%, 21%, and 8% of the U.S. sales, respectively. Trends in use of pesticides in the United States between 1964 and 1997 (55) are shown in Supplemental Figure 1 (54). Supplemental Figure 2 has more detailed information on the past decade (57). (For all supplementary materials, follow the Supplemental Material link from the Annual Reviews home page at http://www.annualreviews.org.) Based on these data, the number of treatments of fungicides per area planted increased between 1991 and 1997.

A U.S. Government Accounting Office study (75) concluded that overall agricultural pesticide use did not decline in the United States between 1992 and 2000. However, the "riskiest pesticides" (including organophosphates, carbamates, and probable or possible human carcinogens) declined by 14% from 206 million kg of active ingredient (ai) in 1992 to 177 million kg ai in 2000. Nonetheless, in 2000, 40% of the total mass of pesticides used in the United States were in the riskiest group. "EPA officials suggested that the decrease [in the riskiest group] may have occurred because some pesticides 1. were discontinued because of EPA regulatory action; 2. were discontinued because of business decisions by the chemical pesticide industry; 3. became noncompetitive compared to newer, cheaper pesticides; 4. became less effective as the target pests developed resistance; or 5. were used less with the introduction of crop varieties genetically modified to resist insects. USDA officials added that use of the riskiest pesticides may have declined because some growers have made progress in implementing nonchemical pest management practices for some crops" (75).

California, the largest and most diverse agricultural producer in the United States, produces more than half of the country's fruits, vegetables, and nuts and uses approximately 22% of the total agricultural pesticides in the nation (58). According to the California Department of Pesticide Regulation, 85 million kg ai of pesticides were applied in California for production agriculture in 2000. Most of the pesticides were applied in seven adjacent counties in the San Joaquin Valley, the state's largest agricultural region. Other agricultural areas with intensive pesticide use include the southern desert valleys in Riverside and Imperial counties, portions of the Sacramento valley, and portions of the coastal region (including Napa, Sonoma, and Monterey counties).

The California Pesticide Use Reports (PUR)

Since 1990, growers and pesticide applicators in California have been required by law to file a Pesticide Use Report (PUR) for each application to a commercial crop (Supplemental note 1). Although these records provide the most comprehensive dataset on pesticide use in the world (12), there are problems with the PUR, including the following: 1. Data quality was initially poor in 1990 but progressively improved through 1992. Although our formal analysis here generally starts in 1993, we note that preliminary analyses that included the data in the first 3 years did not affect our conclusions; 2. As expected for any large database, some errors remain. However, analysis using the individual applicator records (in which errors are detectable) rather than the aggregated data summaries, and careful selection of methods for computation, can minimize the impact of errors on the data; 3. The percentage of compliance with reporting use is unknown. However, there is a penalty for not reporting, and expert opinion is that compliance is high, at least among growers with larger operations; and, 4. The records have no information on pests, pathogens, or cultivars. PUR also has strengths; it is, at least theoretically, a census, not a sample, and consequently shows pesticide use practices of all growers.

We used the individual applicator records to document use of fungicides, fumigants, bactericides, microbial biocontrol agents, and selected insecticides in California between 1993 and 2000 in the field. Except when indicated otherwise, all analyses were for plantings of vegetable, fruit, and nut crops (133 crops). This represents an area of 15.5 thousand km^2 in 2000. Our data-cleaning protocol was based on analyses in previous work (17–19; supplemental text note 2). One application is defined as a treatment of 100% of the area planted, to account for sprays over a several-day period. Most frequently, we show cumulative area treated, which is the total area of application, i.e., if a 1 km^2 area was treated twice, it was counted as 2 km^2 treated.

Trends in Use in California

Use of chemicals to treat plant diseases did not decrease over the past decade. We separated chemicals used to treat plant pathogens (i.e., fungicides, bactericides, and fumigants) into three categories: compounds in use between 1993 and 2000 that are either on "risk" lists or not and compounds that were introduced into agricultural production after 1993. Table 1 lists the total cumulative area treated with compounds on "risk" lists for reproductive toxicity, carcinogenicity, air pollution, and/or acute toxicity. Overall, during the eight-year period, there was no trend towards decreased or increased usage of the pesticides on "risk" lists that are used to control vegetable and fruit diseases in the field. Linear regression estimates of use from 1993 to 2000 are shown; compared to reported use, the slopes, shown as km^2 per year, are comparatively small, and nonsignificant ($P > 0.05$) in all but two cases. The only significant ($P < 0.05$) decline in use detected by linear regression was for triadimefon, a sterol biosynthesis inhibitor; decline was at least partly due to resistance of *Uncinula necator*, the fungus that causes powdery mildew

TABLE 1 The cumulative area of vegetable, fruit, and nut crops treated in California fields between 1993 and 2000 with pesticides that are on "risk lists" that are used to control plant diseases

Compound[a]	Class[b]	Type	Cumulative area treated in year 2000, km^2	Regression estimates, slope in km^2 $year^{-1}$ ± SE[c]	Risks[d]
Benomyl	F	Benzimidazole	826	-22 ± 49	*a*
Captan	F	Phthalamide	1186	114 ± 66	*b,c*
Chlorothalonil	F	Chlorophenyl	1620	-45 ± 80	*b*
Chloropicrin	F, N	Fumigant	188	6 ± 3	*d*
1,3 dichloropropene	F, N	Fumigant	130	21 ± 2^e	*b,c,d*
Iprodione	F	Dicarboximide	2728	-20 ± 69	*b*
Mancozeb	F	Dithiocarbamate	1336	94 ± 81	*b,c*
Maneb	F	Dithiocarbamate	2433	142 ± 93	*b,c*
Metam sodium	F, N	Dithiocarbamate	520	13 ± 15	*a,b,d*
Methyl bromide	F, N	Fumigant	250	-10 ± 7	*a,c,d*
Myclobutanil	F	Triazole	3370	95 ± 94	*a*
Streptomycin	B	Antibiotic	402	6 ± 13	*a*
Thiophenate-methyl	F	Carbamate	172	-16 ± 9	*a*
Triadimefon	F	Triazole	38	-75 ± 8^e	*a*
Vinclozolin	F	Dicarboximide	156	1 ± 7	*a,b*

[a] Only compounds in which more than 25 km^2 were treated in 2000 are shown.

[b] B, bactericide; F, fungicide, N, nematicide.

[c] From 1993 to 2000.

[d] *a*, on California State Proposition 65's "known to cause reproductive toxicity" list; *b*, on either US EPA's B2 carcinogen list and/or the California State Proposition 65's "known to cause cancer" list; *c*, on California Department of Pesticide Regulation's Toxic Air Contaminant list; *d*, classified as acutely toxic.

[e] Slope not equal to 0, $P < 0.05$.

on grapes (31). Use of 1,3 dicloropropene (Telone), a cost-effective substitute for methyl bromide, significantly increased between 1993 and 2000. Although use of methyl bromide is being phased out by a combination of federal regulations and price, its use fluctuated between 1993 and 1999, dropping from an average of 342 km^2 between 1993 and 1999 to 250 km^2 in 2000.

Yearly data for the four compounds in Table 1 that were used on the most area are shown in Supplemental Figure 3. As expected, pesticide use fluctuates from year to year. For many fungicides, usage was higher in 1998 than in the following years. However, the data do not support the hypothesis of a trend in declining use since 1998 (Supplemental note 3).

Similarly, among the 10 compounds (fungicides and bactericides) introduced before 1993 in California that are not on risk lists, and that were applied on more than 50 km^2 in 2000, there is no overall trend towards decreased use (Supplemental Table 1). All of the compounds were used on less than 1000 km^2, except for copper and sulfur, which were applied on 6735 and 24,861 km^2, respectively. Linear regression indicated that there was a significant ($P < 0.05$) decline in use of metalaxyl, but this is due to the loss of metaxyl's patent protection and replacement by the manufacturer with mefanoxam, which is currently patented (Supplemental Table 2). Metalaxyl entered the market in 1977 (37) and is a 1:1 racemic mixture of R and S (2,6-dimethyl phenyl)-N-(methoxy acetyl) alanine methyl ester; mefanoxam contains only the R enantiomer and is consequently essentially purified metalaxyl. As shown in the previous table, there was a significant decline in use of a sterol biosynthesis inhibitor (fenarimol); again, a major use was for control of powdery mildew on grapes. Fenarimol causes phytotoxicity on young shoots in the spring and spotting on fruit; there is also concern about resistance.

RECENTLY INTRODUCED "CONVENTIONAL" COMPOUNDS, INCLUDING "REDUCED-RISK" COMPOUNDS, HAVE BEEN RAPIDLY ADOPTED BY GROWERS Eight new fungicides used to control plant diseases have been introduced and adopted on a significant scale since the start of our study period, i.e., used on more than 200 km^2 in California in 2000 (Supplemental Table 2). In 1993, the US EPA introduced a rapid registration process for conventional but "reduced-risk" pesticides. The five "conventional" reduced-risk materials have diverse histories of development. The meaning of "reduced-risk" is not always intuitive. As indicated above, mefanoxam is essentially purified metalaxyl, and indeed the manufacturer primarily used toxicity data from metalaxyl to register the new compound. Because the R enantiomer provides most of the fungicidal activity, mefanoxam can be used at lower application rates than metalaxyl, and was granted reduced-risk status by EPA. Three strobilurins (3) were introduced into California (azoxystrobin in 1997, and trifloxystrobin and kresoxim-methyl in 2000); the first two were granted reduced-risk status. (Supplemental note 4). Three reduced-risk insecticides also were introduced and rapidly adopted: pyriproxyfen, a juvenile hormone mimic; tebufenozide, a moulting hormone antagonist; and spinosad, a natural product insecticide.

FACTORS, INCLUDING CHANGES IN AREA PLANTED, THAT AFFECTED PESTICIDE USE ON VEGETABLES, FRUITS, AND NUTS IN CALIFORNIA IN THE FIELD It is difficult to assign causes for year-to-year fluctuations in pesticide use. Greater pest pressure or projected profits result in greater pesticide use. Overall, California's dry summer climate inland limits the development of many foliar plant diseases. Consequently, fungicide and bactericide use is less intensive in California than it would be in a region in which rain fell more frequently during the growing season. Indeed, fungicide use is typically lower in years when there is little or no rain in the spring and fall.

PATTERNS OF FUNGICIDE USE ARE CROP DEPENDENT Of the vegetable, fruit, and nut crops in California, the crops with the largest area planted (all with >750 km^2 planted) were almonds, wine grapes, non-wine grapes, processing tomatoes, oranges, and walnuts. Between 1993 and 2000, there was a relatively modest net increase of 5.8% area planted of the selected crops from 16 to 17 thousand km^2. There were increases of approximately 500 km^2 of wine grapes and almonds. There was a decrease in fresh market tomatoes, but an increase in processing tomatoes. Overall, changes in area planted did not have a major effect on usage trends.

TECHNICAL STRATEGIES FOR REDUCTION OF PESTICIDE USE

Rationales for reduction based on pest management and on health and environmental concerns are summarized in Supplemental notes 5 and 6.

Integrated Pest Management (IPM)

Bajwa & Kogan (2) assembled 67 definitions of IPM, and pesticides are mentioned in various ways (http://www.ippc.orst.edu/IPMdefinitions/defineII.html). Not uncommonly, IPM is stated as a method to achieve least pesticide use or risk. The first item of the stated mission of the University of California (UC) IPM project is to "reduce the pesticide load in the environment." As of 2002, the UC IPM web page (http://www.ipm.ucdavis.edu/IPMPROJECT/about.html) states, "Integrated pest management is an ecosystem-based strategy that focuses on long-term prevention of pests or their damage through a combination of techniques such as biological control, habitat manipulation, modification of cultural practices, and use of resistant varieties. Pesticides are used only after monitoring indicates they are needed according to established guidelines, and treatments are made with the goal of removing only the target organism. Pest control materials are selected and applied in a manner that minimizes risks to human health, beneficial and nontarget organisms, and the environment." According to the USDA definition of IPM, ". . .pesticides should be applied as a last resort in suppression systems using the following sound management approach: 1. The cost: benefit should be confirmed prior to use (using economic thresholds where available); 2. Pesticides should be selected based on least negative effects on environment and human health in addition to efficacy and economics. . . ." The American Crop Protection Association states, "well developed, science-based IPM programs have consistently resulted in reduced pesticide use, as they employ a wider array of pest management techniques. IPM programs, by design, result in safer, more judicious use of pesticides." However, the Association also states, "IPM is not a formula to eliminate or reduce pesticide use." Although IPM definitions vary, messages designed for public audiences consistently present IPM as an effective strategy for reduction of pesticide use or risk. Furthermore, review articles regarding pest management often accept without question that IPM is effective in reducing pesticide use or risk (e.g., 44).

IPM AND ITS IMPACT ON PESTICIDE USE In the United States, IPM became a component of federal agricultural policy in 1972 (14). In 1993, the U.S. Department of

Agriculture (USDA), the Environmental Protection Agency (EPA), and the Food and Drug Administration (FDA) declared a goal of implementation of IPM on 75 percent of U.S. crop acreage by the year 2000. The USDA's IPM initiative declares, "This approach to reduction in risks from pesticide use and development of more sustainable agricultural production strategies was adopted by USDA and USEPA rather than the mandated use reduction strategy adopted by several European governments in the early 1990s." By 2000, the USDA estimated that some level of IPM was used on 70% of the U.S. crop acreage. However, the U.S. General Accounting Office (GAO) Report (75) states that although the goal of implementing IPM on 75% of the nation's crop acreage was nearly achieved, "the implementation rate is a misleading indicator of the progress made toward the original purpose of IPM–reducing chemical pesticide use."

Despite messages assuring the public that IPM will reduce pesticide use and result in health and environmental benefits (42, 66), there is no clear consensus among plant pathologists and pest managers that pesticide use should be reduced. In the U.S. GAO Report (75), "a survey of 50 state IPM coordinators indicated that, of the 45 respondents, 20 believed that the IPM initiative is primarily intended to reduce pesticide use, 23 did not, and 2 were undecided." Indeed, implementation of IPM can result in an increase in pesticide use per unit area (7, 23, 60, 80).

Most studies on achievement of policy goals have focused on adoption of IPM, not on any changes in pesticide use. Furthermore, current requirements for achieving IPM practitioner status according to USDA criteria (75) are minimal. No practice disqualifies a grower from qualification. The USDA considers that growers use IPM if they use at least one of a list of practices in three of four categories: prevention, avoidance, monitoring, and suppression. Two acceptable suppression practices are alternating pesticides and use of an herbicide-tolerant crop (75). Ehler & Bottrell (14) criticized current criteria for IPM practice in that there is no focus on integration either for management of a particular pest or for multiple pests. In practice, IPM programs are often dominated by chemical control (11) and are often programs of pesticide management rather than ecologically based pest management (56). Partly as a consequence, some agricultural scientists favor replacing the "integrated" in IPM with terms that either place pest management within a context of agricultural sustainability or emphasize the importance of fully understanding the biology of the pests and the ecology of the agricultural ecosystems (56, 74). Others have suggested that there is a continuum of IPM practice and that IPM that is primarily dependent upon pesticide use is simply "low-intensity" IPM (41, 71).

There are many examples in the literature in which researchers in a study plot have reduced pesticide use compared to "conventional" management (5, 62, 84). The larger question is how implementation of IPM affects pesticide use in the agricultural community. Unfortunately, many of the studies in which the number of pesticidal applications made by growers who do or do not use IPM have small sample sizes and, perhaps consequently, no statistical analysis. (e.g., 48). Moreover, in most comparisons of different farming methods, cooperating growers are neither randomly selected from the population at large nor are they necessarily representative. In particular, given the heterogeneity of grower practices, it would be difficult to identify a sufficient sample of growers that represents the wider population.

IPM can affect patterns of pesticide use that do not involve reduction of use or risk from an environmental or health perspective. The principal effect of IPM adoption on grower programs for insect pests of apples was a change in the specific chemicals used rather than a change in the volume of material applied or area treated (40). In particular, IPM growers used more narrow spectrum materials that caused less disruption to the crop ecosystem. However, the materials were not less risky to humans or animals.

Nonetheless, many IPM practices, at least in theory, could affect pesticide use, including release of pest-resistant cultivars via either genetic engineering or traditional cultivar development, release of natural enemies or biological control agents, release of pheromones or other semiochemicals, and advances in cultural control (43). In a 1994 review, Norton & Mullen (51) concluded, “The picture that emerges from the farm-level evaluation of IPM benefits and costs is one of generally lower pesticide use, production cost and risk, and higher net returns to producers.” However, the reviewed studies on fruits, nuts, and vegetables in California were primarily on insect control in the 1970s or 1980s, during a period in which the mass of insecticides applied decreased in the United States (see Supplemental Figure 1). By the 1990s, IPM was an accepted component of most farming operations in California (71). Whether the current status-quo IPM will result in pesticide reductions is less clear. In an analysis of grower survey data collected by the USDA, Fernandez-Cornejo (24, 25) concluded that in vineyards in six states, IPM adopters applied significantly less insecticides and fungicides than nonadopters. However, adoption of IPM for diseases on grapevines did not affect growers’ “average toxicity” or “Environmental Impact Quotients,” although these values were decreased slightly for adopters of insect IPM. Nonetheless, the adopters of IPM for diseases had higher yields and profits, whereas adopters of IPM for insects did not.

Using literature reviews and telephone interviews, we sought examples in which (*a*) a researcher thought that an IPM program in California during the 1990s had resulted in reduced use of fungicides or bactericides and (*b*) the PUR data supported the contention. We found no examples for plant diseases or for herbicide reduction. However, there are a few examples from California in which use of organophosphates (OPs) has been reduced, primarily by substitution with pyrethroids (18, 19). Even with the far greater number of IPM programs for insects than diseases, examples of declines in insecticide use during our study period were relatively infrequent. A case study on the decline in use of OPs in almond and stone fruit orchards used during the dormant season (18, 19) is summarized below.

A CASE STUDY ON PESTICIDE USE: REPLACEMENT OF A WINTER APPLICATION OF AN ORGANOPHOSPHATE INSECTICIDE ON ALMOND AND STONE FRUIT TREES In California, regulatory agencies have been concerned about OP contamination of surface water and consequent violation of the Federal Clean Water Act. OP contamination originates in part from applications on dormant almond and stone fruit orchards; the OPs are washed off during winter rainstorms. Interestingly, when dormant-season applications were introduced in the early 1970s (68), they were viewed as an environmentally sound practice, because one application during the dormant season potentially replaces multiple applications during the growing season. Also, an application of an OP during the dormant season has other environmental advantages over an in-season application: fewer adverse affects on beneficial arthropods, less exposure to field workers, and no exposure of fruit to potential residues. However, during the 1990s, in response to food safety groups, regulatory agencies began to critically examine the health and environmental effects of OP use. Currently, programs funded by the University of California Statewide Integrated Pest Management Project and the Biologically Integrated Orchard Systems (BIOS), a coalition of public and private groups, have promoted the replacement of use of OPs on almonds during the rainy season with alternative practices. There has been less educational effort in the nectarine, peach, and plum industries. In addition, there are different cosmetic standards for these stone fruits than for almonds.

We examined dormant-season practices in almonds and stone fruits (nectarine, peach, plum, and prune) orchards and found that the three years of highest use of dormant-season OPs were typically from 1992 to 1994, and then declined (Supplemental Figure 4). However, the decline in use of OPs has been accompanied by an increase in use of pyrethroids, which are competitively priced with OPs, particularly in stone fruit orchards (Figure 1). The data also indicate that a substantial area in almond orchards was not treated with either OPs or with other conventional pesticides, and that the area of almond orchards treated with "sustainable" alternatives increased. In contrast, in stone fruit orchards, there was no overall change in the percentage of area treated either with any of the reduced-risk treatments or in which there was no dormant treatment. Despite the reductions in dormant-season OPs, large quantities of OPs were still applied in dormant orchards. In 2000, on the almond orchards in 11 counties and in the 16 county-stone fruit combinations, approximately 19,000 and 49,000 kg of dormant-season OPs were applied, respectively. Areas planted in 2000 for those county-crop combinations were 1800 km^2 for almond and 650 km^2 for the stone fruit. Whether there will be new pest or environmental consequences of increased use of pyrethroids is unknown (76, 85).

A CASE STUDY ON PESTICIDE USE: POWDERY MILDEW ON GRAPES

Growers vary greatly in their intensity of fungicide use and, in 1995, most growers used less than recommended by a "calendar spray model" Conidia of the fungi that cause powdery mildews do not require free water to germinate, and consequently powdery mildews are major diseases in California. In particular, powdery mildew (PM) is the major disease of grapevines and is a perennial threat to crop production

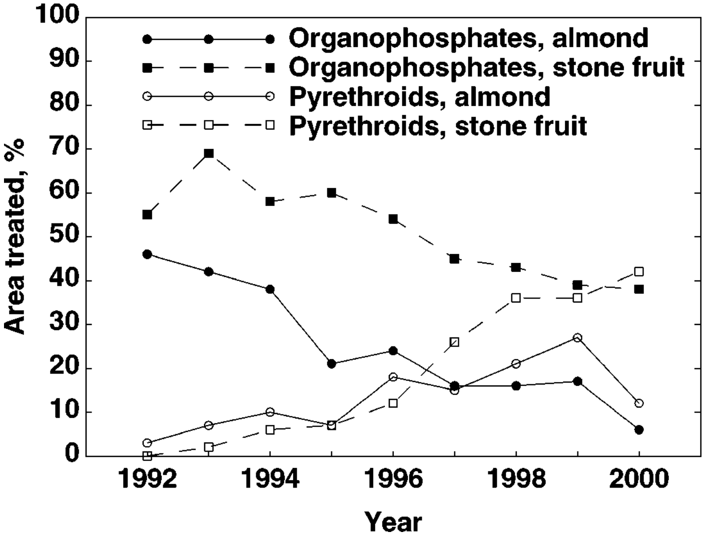

Figure 1 Percentage of area treated during the dormant season with organophosphates and with pyrethroids in almond and stone fruit orchards from 1992 to 2000. The data include orchards in counties in California in the Sacramento Valley, and in the Northern and Central San Joaquin Valley with at least 25 km^2 of almond (Butte, Colusa, Fresno, Glenn, Madera, Merced, San Joaquin, Stanislaus, and Tehama) and of any of the following stone fruits: peach (Fresno, Merced, Stanislaus, Sutter, and Yuba); prune (Butte, Glenn, Sutter, Tehama, and Yuba), plum (Fresno), and nectarine (Fresno). (Updated from Reference 18.)

in all grape-growing regions in the state (27). The pathogen, *Uncinula necator*, is controlled by multiple applications of fungicides and the fungicides used to control powdery mildew generally differ from those used to control other diseases. Given that California has approx 2900 km^2 of vineyards, more fungicides are used to control powdery mildew on grapes than any other disease on any crop.

In the major grape-producing counties, we used each grower's PUR records to calculate the minimum days of protection (DOP) that their fungicidal applications would have provided against powdery mildew using the application intervals from a "calendar spray model" (Supplemental note 7). For each county and type-of-grape, growers were ranked according to their total DOP per km^2 planted. In Figure 2, the solid lines show the minimum DOP of a grower at the indicated percentile for each year. For example, in 1995, 95% of the growers in Sonoma County had a minimum of 134 or less DOP. In 1996, Gubler & Thomas introduced a temperature-driven model for PM in which the spray interval was extended, depending upon the temperature and the fungicide (http://www.ipm.ucdavis.edu/DISEASE/DATABASE/grapepowderymildew.html; 32). Under the highest disease pressure, the calendar spray and the temperature-driven models recommend the same fungicide

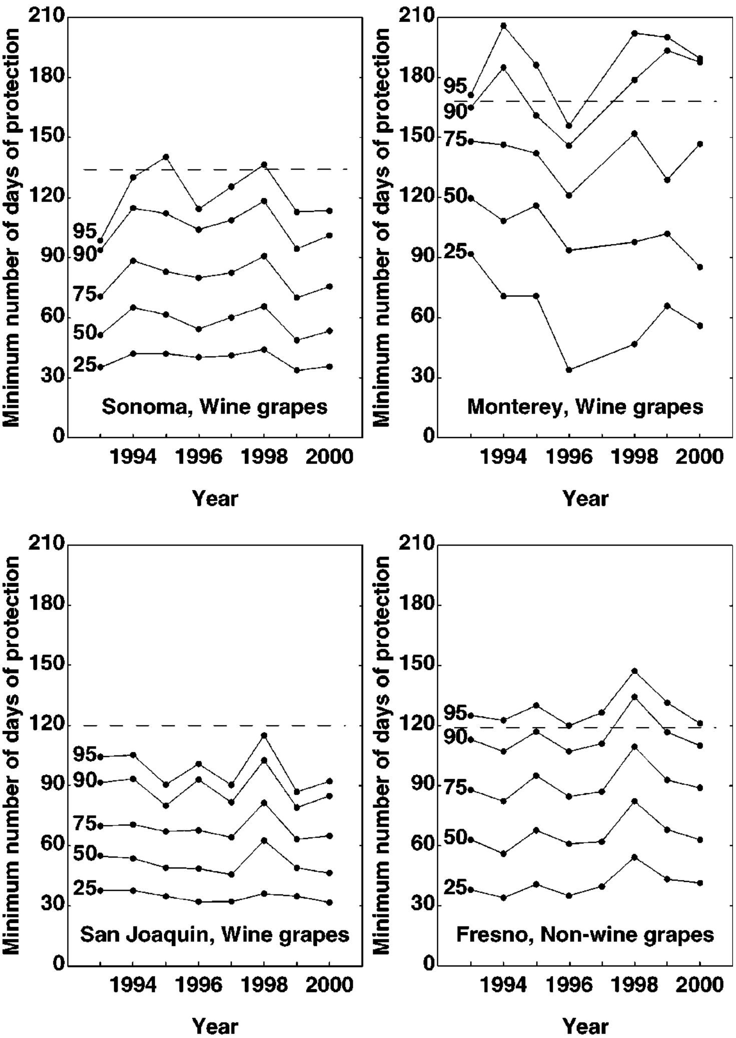

Figure 2 The minimum number of days that grapevines were protected from *Uncinula necator*, causal agent of powdery mildew of grapes in selected California counties from 1993 to 2000. Based on individual applicator records from the Pesticide Use Reports, the solid lines show the days of protection provided by a grower in the indicated percentile, using the "calendar spray model," i.e., for high disease pressure conditions. The dashed lines show the typical number of days necessary for protection of the more susceptible varieties from powdery mildew. For each grape-growing region in California, the county with the largest area planted is shown.

application program, but in temperatures in which the disease pressure is less, the temperature-driven model recommends fewer applications. The length of the season during which plants require protection from powdery mildew varies with the region and cultivar (27; personal communications with Cooperative Extension personnel). The dashed lines in Figure 2 show the typical number of DOP required for control of powdery mildew on the more susceptible cultivars in the different regions in California (Supplemental Table 3). Empirical testing of the temperature-driven model in California indicated that the growers following the environmentally driven model generally used one to three fewer applications depending upon the location (32, 73); this would correspond to a decrease in the indicated DOP of at most 21 days. However, in Monterey County, disease pressure is so high throughout the season that recommendations from the environmentally driven model and the calendar spray model are the same.

Disease-forecasting models can reduce pesticide use as projected only if growers are currently using a calendar-based application schedule and if implementation of an environmentally driven model would allow growers to use less chemical with the same or better control (1). Assuming that growers are not grossly underreporting use, we show that growers within a county use extremely heterogeneous pesticide application programs. In 1995, for example, more than 79% of the growers in every county were using less fungicide than recommended by the calendar spray model (Supplemental Table 3). That is, most California vineyards appear to be applying fungicides judiciously, and the question arises of whether the low users have adequate or optimal disease control. Whereas the environmentally driven model would potentially allow reductions in use by growers whose DOP is above, or up to 21 days below, the DOP recommended by the calendar spray model, pesticide use will only decline if the low users do not increase their use. However, we note that fungicide use has been fairly stable since the environmentally driven model was introduced (Figure 2).

Microbial Biocontrol Agents (MBA)

THERE IS LIMITED USE OF MICROBIAL BIOCONTROL AGENTS TO CONTROL PLANT DISEASE IN PRODUCTION AGRICULTURE IN CALIFORNIA, AND NO INDICATION OF AN INCREASE Biological control has been an active area of plant pathology research for many years. Commercial microbial biocontrol products available in the United States are summarized in McSpadden et al. (49). In California, all pesticidal products used in production agriculture must be registered with the state Department of Pesticide Regulation, and registration of biocontrol products has been streamlined. Only five microbial biocontrol agents were applied in the field on at least 7.5 km^2 in any of the study years: *Bacillus thuringiensis*, used to control lepidopteran insects; *Ampelomyces quisqualis* used to control fungi that cause powdery mildew; *Agrobacterium radiobacter* and *Pseudomonas fluorescens* to control bacterial pathogens; and *Myrothecium verrucaria* to control nematodes. Other microbial biocontrol agents that were registered but used on less than 7.5 km^2 in all years include *Bacillus sphaericus*, *Beauveria bassiana*, *Gliocladium* *virens*, *Lagenidium giganteum*, *Nosema locustae*, *Pseudomonas syringae*, *Streptomyces griseoviridis*, and *Trichoderma harzianum*. We note that our analyses are for compounds applied "in the field" and may not include records of products used as seed treatments.

The cumulative area treated with each microbial biocontrol agent is shown in Figure 3. In 1997, *B. thuringiensis* was applied on 4323 km^2 of vegetables and tree crops whereas all of the other microbial biocontrol agents used for plant disease (MBA-PD) combined were applied on only 4% (187 km^2) of as much area. Although the total area treated is relatively small, there were increases in use between 1993 and 1997, i.e., some growers tried the MBA-PDs. However, between 1997 and 2000 there was a 68% decline in use of MBA-PD. It is less clear whether the 20% decline in use of *B. thuringinesis* between 1997 and 2000 is a fluctuation or a trend. The net decrease of 851 km^2 treated with *B. thuringinesis* between 1997 and 2000 was primarily caused by reductions on 11 crops including almonds, lettuce, broccoli, and fresh market tomatoes. The net decline occurred despite the fact that with three crops (wine grapes, strawberries, and processing tomatoes), there was an increase in 457 km^2 treated. In cases in which use of *B. thuringinesis* increased, there are expanding organic markets with some limitations in pest management alternatives (72). In contrast, whereas organic growers could control powdery mildew with *A. quisqualis*, they also can control the pathogen with sulfur and/or copper. *Agrobacterium radiobacter* K84, the classic success story for MBA-PD, is used to control *A. tumefaciens*, causal agent of crown gall on fruit and nut trees. However, in some cases, *A. radiobacter* has failed to control

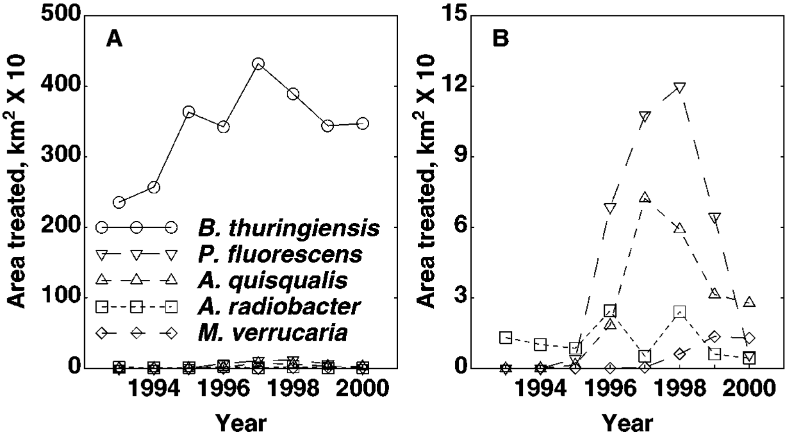

Figure 3 For vegetables, fruits and nut trees, the cumulative area treated with microbial biocontrol agents in California from 1993 to 2000. Any agents applied onto more than 7.5 km^2 in any year are shown. *B* does not include *Bacillus thuringiensis* and is scaled 33 times the one shown in *A*. Data are from the California Pesticide Use Reports.

crown gall on walnuts in California, possibly because the nursery stock were either infested or infected with *A. tumefaciens* before treatment.

GROWERS WHO USED THE ANTI-BACTERIAL MBA-PD PSEUDOMONAS FLUORESCENS DID NOT REDUCE THEIR ANTIBIOTIC USE *Pseudomonas fluorescens* A506 (Blight Ban) is used to control three pathogenic conditions: fire blight, caused by *Erwinia amylovora*; blossom blast, caused by ice-nucleating strains of *Pseudomonas syringae*; and russetting, caused by various indole acetic acid-producing bacteria (46, 47, 79). A research and extension program at the University of California, and financial support from the California growers' Pear Advisory Board, were instrumental in introducing *P. fluorescens*. In 1998, most (78%) of the area treated with *P. fluorescens* was planted with pears; the remainder was planted with apples. For a MBA-PD, use of *P. fluorescens* on pear trees was high; 29% of the area planted was treated with *P. fluorescens*. Of the sites with pears in which *P. fluorescens* was used, the median number of applications was three per year. The decline in use in *P. fluorescens* in 1999 and 2000 was at least partly due to lack of an available product of expected quality. Declining profits in the pear industry may have also been involved.

In California, organic growers can use streptomycin, oxytetracycline, copper, and Bordeaux, in addition to *P. fluorescens,* to control fire blight. A goal of the use of *P. fluorescens* is to reduce antibiotic use (15) and consequently, use of *P. fluorescens* on pears offers an opportunity to determine whether growers who incorporate a MBA-PD into their control program reduced their use of antibiotics. We note that *P. fluorescens* is not necessarily used as a replacement for antibiotics. Indeed, *P. fluorescens* can be tank-mixed with streptomycin. We selected all the pear growers ($n = 89$) who could be tracked over the four-year period from 1995 to 1998 (Supplemental note 8) and classified them into one of three groups: those who made no applications of *P. fluorescens* in all of the four years ($n = 40$) (Figure 4), shown as open circles; those who made no application of *P. fluorescens* in 1995, but made at least one *P. fluorescens* application in both 1997 and 1998 ($n = 15$), shown as filled-in circles; and those who did not fit into either of the other two categories (not shown). The data indicate that growers with the most intensive antibiotic use were more likely to try *P. fluorescens* ($P = 0.012$ for logistic regression). Overall, growers who tried *P. fluorescens* used it in addition to their antibiotic treatments and not as a replacement.

As a contrast to the decrease in use of microbial biocontrol agents from 1998 to 2000, we present data on the increase in use of pheromones to control insects by mating disruption (Supplemental Figure 5). The area treated increased from 110 km^2 in 1998 to approximately 375 km^2 in 1999 and 2000. Most of the use in 2000 was on six crops (Supplemental Table 4). Grant support from the USDA, the California Department of Pesticide Regulation, and the University of California Sustainable Agriculture Research and Education Programs subsidized growers' purchase of the pheromones. Continued subsidies would assure greater pheromone use and a resultant replacement of some insecticide applications.

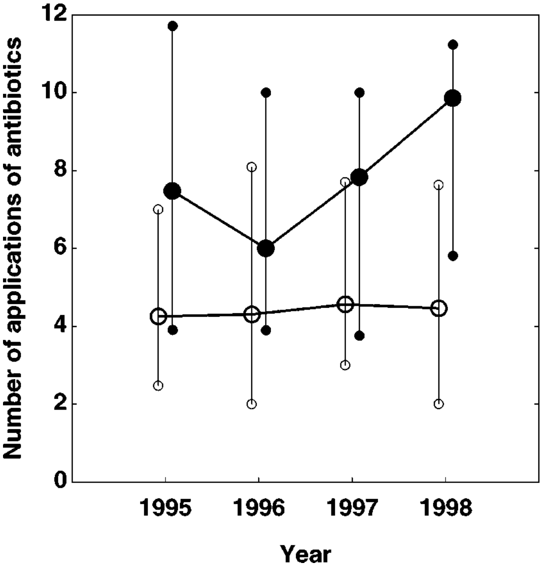

Figure 4 The larger circles show the median number of applications of antibiotics by pear growers; the smaller circles below and above show the first and third quartiles of use. Applications were computed as the cumulative area treated divided by the area planted in pear orchards in California between 1995 and 1998. Individual sites that were owned by the same grower and that could be monitored year to year were selected from the Pesticide Use Reports. For each grower, the microbial biological control agent *Pseudomonas fluorescens* was never used between 1995 and 1998 (○), or at least one application of *P. fluorescens* was made in 1997 and in 1998, but not in 1995 (●).

Genetically Modified (GM) Plants: Impacts of GM Plants in Commercial Production on Pesticide Use

GM crops have been portrayed to the public and within the scientific community as a successful strategy for pesticide reduction (22, 29, 61) and indeed there appears to be great potential. However, in the case of GM for resistance to plant pathogens, as of 2002, the only commercial plantings were papayas in Hawaii with resistance to *Papaya ringspot virus* (30). The transgenic trees have saved the papaya industry in Hawaii, but since pesticides were never used to control the disease, there was no reduction in pesticide use.

Interpretation of data on changes in herbicide use after introduction of glyphosate- and bromoxynil-tolerant (HT) crops are somewhat complicated, and whether HT crops have reduced herbicide use has been debated (4). HT plants are engineered to withstand post-planting herbicide applications, which theoretically allow more in-season herbicide applications on an HT crop (35). In addition, if herbicide use is calculated in mass, glyphosate is used at a higher concentration than many other herbicides. Nonetheless, USDA studies have concluded that there was a slight decrease in the number of herbicide treatments per unit area planted with HT crops, although not in all regions, and there was an increase in mass of herbicides applied (26). Regardless, glyphosate is among the safest of herbicides for mammals and the environment, and there is less pesticide run-off from planted fields than from bare ground (20). In addition, herbicide-tolerant plants allow no-till farming, which exacerbates some disease problems (6) but reduces soil erosion and use of fossil fuels in plowing. However, there may be some problems with HT crops. There appears to be an approximately 5% yield reduction in HT plants compared to their nontransgenic controls (16).

Changes in insecticide use after introduction of crops that produce the *B. thuringiensis* (Bt) toxin are somewhat crop dependent. Introduction of Bt-cotton has resulted in lower insecticide use (26, 39, 64). Declines in pesticide use associated with the adoption of Bt-cotton in California are shown in Supplemental Figure 6 and Supplemental Table 5 (Supplemental note 9). Whether Bt-corn has reduced insecticide use on corn is a matter of debate (52, 53) partly because economic damage from the European corn borer (ECB) only occurs in some years and most growers never applied insecticides for ECB control. Regardless, as with pesticides that have a single biochemical site of action, the development of resistance of pests to Bt-toxin is of concern. Although producers of Bt-crops have resistance-abatement programs, the development of resistance of pests to Bt-toxin is generally considered a matter of time (9a).

Pesticides can reduce the potential for mycotoxin production. Corn that is genetically modified with the Bt-toxin is less frequently invaded by the ECB. Since the borer provides wounds for the mycotoxin-producing fungi *Fusarium verticillioides* and *F. proliferatum*, transgenic corn had less fumonisin (50). Nonetheless, sublethal concentrations of some fungicides and insecticides enhance production of some mycotoxins and consequently, pesticidal compounds in plants could, in theory, also increase mycotoxin production in some host-pathogen interactions (13). In particular, D'Melo et al. (13) suggest that fungicide resistance in *Fusarium culmorum* may be accompanied by more persistent mycotoxin production.

SOCIAL STRATEGIES FOR PESTICIDE REDUCTION

Mandated Reduction, Loss of or Restricted Registration, Taxation, and Attrition of the Older Chemistries

Obviously, there is decreased use of compounds that have been discontinued or phased-out. Several countries in Europe have implemented mandated reductions, with a resultant switch to compounds that are used at lower application rates (21). However, use of pesticides in Europe is still generally higher than in the United States. Under the Montreal Protocol and Subsequent Agreements, and the Clean Air Act, methyl bromide will be phased out, using an economic mechanism of increased taxation. In 1996, the U.S. Congress passed The Food Quality Protection Act (FQPA), and amended the Federal Insecticide, Fungicide, and Rodenticide Act

(FIFRA) and the Federal Food, Drug, and Cosmetic Act (FFDCA). Under FQPA, EPA must complete a reevaluation of pesticide tolerances by 2006, with the riskiest pesticides evaluated first (70). After EPA evaluates OP insecticides, carbamates will be evaluated. Fungicides that may be affected by FQPA include thiram, fenarimol, and ziram. However, as of November 2002, most decisions regarding FQPA that affect allowable fungicide use concern turf grass applications in residential and public areas and on golf courses. In California, township-wide use of the fumigant 1,3 dicloropropene (1,3-D) is limited because of air quality regulations, and consequently grower demand for 1,3-D as a methyl bromide replacement will likely be greater than its availability (8).

By 2002, 75%–85% of the major pesticides were off patent. For pesticide manufacturers, the costs of meeting regulatory requirements for re-registration may be burdensome. In 2001, the manufacturers of benomyl voluntarily cancelled their registration, citing excessive costs for both re-registration and for settlement of multiple lawsuits (83). Lawsuits were brought primarily by disgruntled growers who used benomyl and claimed phytotoxicity, but lawsuits, e.g., by a shrimp producer who claimed he was adversely affected by benomyl run-off from a banana plantation and one claiming birth defects, were also mentioned as costing the manufacturer too much money (83).

Processor-Mandated Requirements

Some food processors restrict growers' pesticide use. For example, Sun-Maid™ requires that its raisin growers submit application reports and prohibits use of registered pesticides that are of greatest concern to consumers, i.e., selected insecticides (azinphos-methyl, dicofol, dimethoate, ethion, malathion, and methyl parathion) and fungicides (benomyl, captan, iprodione, mancozeb, maneb, and triadimefon). The impacted fungicides are primarily used for bunch rot control. Wineries in California are concerned that sulfur residues may inhibit fermentation, and consequently have been extending the time period between the last acceptable sulfur application and harvest; this reduces the time period in which growers who rely on sulfur, the least expensive fungicide, can apply chemical protectants for powdery mildew.

Consumer-Driven Strategies, e.g., "Organic" Agriculture

During the 1990s, organic agriculture was one of the fastest growing segments of Californian, U.S. and European agriculture (72). Approximately 2% of California's farmland is organic. Lower yields are often reported in organic plots, but grower profits are often equal because there is a premium price for organic products (78). However, in a comparison of organic, conventional, and integrated apple production systems in Washington state from 1994 to 1999, Reganold et al. (67) found equivalent yields in all systems, with highest profitability and greater energy efficiency in the organic than in the other systems. Nonetheless, if organic production increases, standard economic theory suggests that an increase in the supply of organic produce would result in a lower price, which would in turn reduce the profitability of organic relative to conventional produce (45). Also, postharvest losses may be higher for many organic fruits and vegetables than for conventional ones, which would make them more expensive even if harvested yields were comparable.

Voluntary Grower Efforts

The data shown in Figures 2, 4 and Supplemental Figure 4 indicate there is great heterogeneity in pesticide practices among growers. Finding mechanisms to increase the population of growers with lower pesticide use may provide the greatest opportunities for reduction of pesticide use or risk. For example, providing incentives for growers to plant disease-resistant cultivars in areas with comparatively low disease pressure may provide a new strategy for pesticide reduction. In California, starting in 1993, 238 growers joined two programs, the Biologically Integrated Farming Systems (BIFS) and Biologically Integrated Orchard Systems (BIOS); the goals of both projects include pesticide reduction (72). The projects are funded by federal and state agencies and by private foundations and, over time, have included 108 km^2 of demonstration projects. Participating growers have greater access to expertise in pest management. Whether growers who joined the program already had a lower pesticide use than the “conventional” growers from the wider community, or whether growers who enroll in the program reduce their pesticide use or risk, remains to be demonstrated.

IMPEDIMENTS TO PESTICIDE REDUCTION

Uncertainty of Epiphytotics and Subsequent Prophylactic Use

Although some fungicides have systemic or localized activity, many fungicides are primarily protectants and must be applied prophylactically. Although disease models may improve, there are large error terms associated with the probability of disease incidence. Moreover, whereas economic thresholds are key components in models used to recommend applications for insect control, economic thresholds are not a component of current models for plant disease. That is, fungicide use is generally not driven by the presence of disease, but rather by the perceived risk of disease or the consequences of disease that occurred in previous years.

Differing Cost-Risk and Benefit-Risk Analyses for Growers, Pest Management Advisers, Pesticide Corporations, the Public, and the Environment

IPM is presented as a strategy in which the benefits both to growers and to society are maximized and risks are minimized (41). However, this contention is based on the assumption that all “stakeholders” bear the same costs and risks, and share the same benefits. In fact, growers as individuals bear potential profit loss both from expenditures associated with using more pesticides than necessary and from crop loss associated with undertreating. Whereas consumers, environmental groups, and society at large may face increased food costs associated with widespread crop failure, they do not face risk associated with crop loss to an individual grower. In 1968, Headley (36) calculated the benefit-cost ratio to society of pesticides is 4:1; a figure cited widely. However, numerous authors have contended that the calculations are economically too simplistic and that "externalities" (costs borne by the public or future generations) were ignored. More recent studies have indicated that pesticides have benefit-cost ratios of 1.3:1 (63) and 1.5:1 (82). Regardless of the actual benefit-cost ratio to the public, in contrast to agriculture, IPM programs in schools (http://www.cdpr.ca.gov/cfdocs/apps/schoolipm/main.cfm) may have greater success in reducing pesticide risk or use, because there are fewer conflicting interests among the stakeholders.

In the agricultural economics literature, there is debate about whether pesticides are risk-reducing or risk-increasing, but "risk" is often used in the technical sense of whether pesticides decrease or increase profit variability, not whether pesticides, on average, increase or decrease profits (45). In the pest management literature, the term "risk" is sometimes used in the same way (59). Based on a study that monitored growers' use of pesticides, and disease and insect incidence in apples, Penrose et al. (60) used anecdotal evidence to suggest that "acceptance of risk accounts for a large proportion of the differences in pesticide use in different orchards." However, in the pest management literature, the term "risk" is also used to mean a variety of concepts: the uncertainty of the infestation itself; the uncertainty of whether an IPM technique will be as effective in controlling pests as a calendar-spray program; and a grower's profit risk by either applying too few pesticides and losing crop revenue or of unnecessarily increasing costs by applying more pesticides than necessary.

Although reduction of unnecessary or cost-ineffective pesticidal applications is an economic benefit to growers, in many cases, a decrease in pesticide use must be accompanied by an increase in cultural control practices if adequate pest management is to be maintained. Cultural practices often are more labor-intensive than pesticide applications (9). Although the pesticide price index increased in the United States by 19% between 1991 and 1997, the wage index for agricultural labor increased by 22% (54). Thus, in a time of declining crop prices, it may not be economic for individual growers to reduce their reliance on pesticides. Nonetheless, economic analyses for growers or society as a group may indicate that nonpesticidal methods such as breeding are more economically efficient than pesticides (77).

We submit that the worst situation for pest-control professionals is to have a client follow their advice and then suffer the economic consequences of a pest outbreak. Consequently, pest-control professionals tend to recommend treatment for "worst case" scenarios. Sites for field trials used by Cooperative Extension personnel to test application schedules and rates of pesticides are often selected in areas in which pest pressure is very high so that the recommendations will be effective in the worst of circumstances. Similarly, pesticide companies have an economic interest in having sufficient material applied to avoid liability for lack of pest protection in the conditions with the most severe pest pressure.

In California, pest control advisers are licensed by the state and work as either independent contractors, in-house employees of large farms, or, most commonly, employees of pesticide companies. Most employees of pesticide companies receive commissions based on sales. In a study between 1970 and 1974, cotton and citrus growers in California who followed the advice of private pest management consultants used between one third and two thirds fewer pesticide applications than growers who followed the advice of chemical salesmen (33, 34). Similarly, in a study conducted in 1996 of vegetable and fruit growers, three quarters of growers using independent pest control advisers reported that they had either reduced the amount of sprays used, changed spray timing, or shifted to less toxic sprays in comparison to one quarter of the growers who used an adviser employed by a chemical company (71).

Policy Barriers

Federal farm policy is not always consistent with goals of pesticide reduction (54). Farmers who rotated crops did not qualify for funding under the 1985 Farm Bill (81). There are federally subsidized crop insurance programs for most crops in California, and for those crops, the majority of California growers purchase insurance. Currently, the deductibles are sufficiently high (25–50%) that most claims are made for losses due to weather rather than for losses from disease or pests. However, damage from insects and disease is covered only if standard procedures are used, including pesticide use. Indeed, corn growers in the U.S. corn belt who purchased crop insurance used more insecticides and more herbicides than those who did not purchase insurance (38). Although federal insurance is starting to recognize organic practice as a management practice for organic farmers, the insurance does not cover losses related to IPM implementation (75). The GAO report suggests that federal crop insurance could provide a mechanism for reducing risk associated with adopting IPM.

In addition to federal insurance, loans and insurance in the private sector also generally require farmers to follow best management practices, which include pesticide applications, to qualify for insurance indemnities.

CONCLUSIONS

Data from the California Pesticide Use Reports indicate that agricultural usage of fungicides, bactericides, and fumigants was fairly constant throughout the 1990s with generally rapid acceptance by growers of new, “conventional” fungicides. The U.S. public appears to want a reduction in agricultural pesticide use or risk, and has been told that IPM is the means to achieve that end. Although IPM is a politically viable concept that appeals to a broad cross-section of interest groups, we suggest that that it is unlikely to result in much pesticide reduction in California in the next 10 years, partly for the following reasons: IPM use is not measured in terms of pesticide practices; in practice, effective and economic pest management receives higher priority among IPM personnel than pesticide reduction; and providing growers with economical, nonrisky alternatives to their current chemical control practices will require greater long-term institutional support than is currently available. Alternative management procedures to chemical fumigation are particularly needed. In California, as a result of sustained efforts by Agricultural Experiment Station researchers in collaboration with Cooperative Extension personnel and the support of grower commodity groups, there are a few programs in which pest control practices have changed. Better assessments of the potential profit loss to a grower for applying or not applying pesticides are needed. Genetically modified (GM) crops, as well as crops that are traditionally bred for resistance, have the potential to reduce pesticides. However, for long-term effectiveness, development of GM crops with genes for pest resistance must be developed within a context of sustainable agriculture, and the gene pool of crop plants needs to be maintained.

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