Chapter 7
The Impact of Integrated Pest Management Programs on Pesticide Use in California, USA

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Contents

Abstract Integrated Pest Management (IPM) is often promoted to farmers as a method that can provide the most economical, sustained disease and pest control, but promoted to the public as a method to reduce agricultural pesticide use. California has a public infrastructure for supporting IPM research and implementation, largely through the University of California IPM program. California's Department

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of Pesticide Regulation's Pesticide Use Reports provide a system to track pesticide use state-wide. In practice, IPM in California is extremely pesticide-dependent, particularly in weed control and in agricultural production systems that rely on soil fumigation, such as strawberries. During our study period between 1993 and 2010, California had a decrease in use of 88 % of the highly-used pesticides listed for regulatory concern for human health. However, most of these pesticides were replaced with other chemicals rather than with non-chemical methods. We feature several case studies that illustrate key issues in California IPM: the limited progress in meeting Montreal Protocol guidelines for methyl bromide phase-out due to critical use exemptions for strawberry producers; a successful IPM program to decrease use of dormant-season organophosphates that are important water pollutants; the increase in use of neonicotinoid insecticides, which might have a role in the current bee colony collapse disorder; and the limited use of all of the commercialized microbial biocontrol agents except for *Bacillus thuringiensis*.

Keywords Agriculture · Biological control · Fumigants · Fungicides · Herbicides · Insecticides · Methyl bromide

7.1 Trends in Agricultural Pesticide Use in California from 1993 to 2010

7.1.1 Monitoring Pesticide Use with the California Pesticide Use Reports

Here we show trends in agricultural pesticide use from the California Pesticide Use Reports (PUR) database, an extensive pesticide reporting system that started in 1990 and achieved reasonable data quality in 1993 (Epstein 2006). According to California law, (http://www.cdpr.ca.gov/docs/legbills/calcode/subchpte.htm#pur), all commercial agricultural pesticide use in California must be reported weekly to county agricultural commissioners, who then forward the data to the California Department of Pesticide Regulation (DPR). Pesticide applications to schools and day care facilities, parks, golf courses, cemeteries, rangeland, pastures, and along roadside and railroad rights-of-way are also reported but on a monthly basis, as are postharvest pesticide treatments of agricultural commodities and pesticide treatments in poultry and fish production and in some livestock applications. Home-and-garden use and most industrial and institutional use are exempt from reporting. Each PUR record contains information on the following: a grower identification code with an indication of whether a grower or a commercial pest control operator filed the report; the crop treated; the number of acres of the crop that the grower planted; the grower's identification of the particular field treated (the site location identification); the geographic location (township, range and section) of the treated field to within a square mile (2.59 km^2); the county code; the application date; the active ingredient; the number of acres (or other units, 1acre = 0.405 ha) treated; the pounds (1 pound = 0.45 kg) of active ingredient applied; the pesticide product used; the formulation; the pounds of product applied; and application method (by air or on the ground).

Individual records and summaries of the PUR are available from DPR (http://www.cdpr.ca.gov/docs/pur/purmain.htm). The California Healthy Schools Act of 2000 established specific right-to-know requirements for pesticide use in public schools (Barnes et al. 2012). Although there are errors in the PUR that can be addressed in a variety of ways (Epstein et al. 2001; Epstein 2006), the PUR remains the most comprehensive pesticide use reporting system in the world.

7.1.2 General Trend of Decreasing Use of Chemicals of Regulatory Concern

Table 7.1 shows trends in the mass of major agricultural pesticides of major regulatory concern that were applied in California between 1993 and 2010. The table includes data for 48 compounds that were applied in relatively large quantities in agriculture (i.e., more than 10,000 kg in either 1993 or 2000), and that appear on at least one of five lists: the California State Proposition 65 (CP65) list of reproductive toxins; either the CP65 carcinogen list or the U.S. EPA B2 probable carcinogen list; the U.S. Food Quality Protection Act list of organophosphates and carbamates; the DPR groundwater protection program list of compounds; and the DPR toxic air contaminants list as of 2010. Of the 49 compounds in Table 7.1, 43 (88 %) have declined in use, and have been at least partially replaced by materials of lesser regulatory concern. Nonetheless, only three (benomyl, cacodylic acid, and cyanazine) of the 43 compounds with declining use, or 7 %, are no longer in use, while others are still used extensively. Two (methyl bromide and metam sodium), or 5 % of the 43 compounds, have current annual use (averaged over the 2008–2010 period) of 2.2 and 4.4 million kg, respectively, while another 42 % have annual use in the 10^5 kg range and 37 % have annual use in the 10^4 kg range. Thus, despite use reduction these pesticides remain of considerable regulatory concern.

The U.S. Food Quality Protection Act has been an important driver of changes in organophosphate (OP) and carbamate usage in California and in the U.S. (Van Steenwyk and Zalom 2005). In the U.S., OP use declined from approximately 59 million kg in 1980 to 38 million kg in 1990, and then vacillated around this level until 2001 (Grube et al. 2011). Starting in 2002, OP use declined further to 15 million kg in 2007. As suggested in Table 7.1, OP use has declined in multiple crops in California. PUR data has been used to show declining use of OPs in pears (Weddle et al. 2009). In Sect. 7.3.1 we discuss data on declines in OP use in dormant almond and stone fruit orchards in California. Zhang and Zhang (2011) used PUR data to show a declining use of the most toxic miticides by California winegrape growers.

California has avoided certain environmental issues by never registering some of the pesticides that are commonly used in the rest of the U.S. In 2007, the herbicide acetochlor was the 5th ranked most commonly used agricultural pesticide in the U.S. (Grube et al. 2011). However, acetochlor is on the CP65 known carcinogen list, and is not registered in California.

Table 7.1 Trends in use of the main pesticides of regulatory interest that were used in agriculture in California between 1993 and 2010[a].

Agricultural use	Compound[b]	Annual average applications, kg			Linear regressions, 1993[c]–2010, if $R^2>0.50$		Risk groups[b]
		1993–1995	2008–2010	% change	Slope, kg/yr	R^2	
Defoliant	s, s,s-Tributyl phosphorotrithioate	4.2×10^5	6.2×10^3	−99	-2.7×10^4	0.91	N, A
Fumigant	*Chloropicrin*	1.1×10^6	2.6×10^6	*+130*	1.0×10^5	0.96	A
Fumigant	*1,3-Dichloropropene*	7.1×10^4	3.7×10^6	*+5120*	2.7×10^5	0.86	C, A
Fumigant	*Metam potassium*	0	2.2×10^6	*(new)*	2.3×10^{5}[c]	0.88[c]	A
Fumigant	Metam sodium	5.3×10^6	4.4×10^6	−17	–	–	R, C, A
Fumigant	Methyl bromide	7.5×10^6	2.3×10^6	−69	-3.8×10^5	0.85	R, A
Fungicide	Benomyl	1.4×10^5	2.8×10^1	−100	-9.6×10^3	0.59	R
Fungicide	Captan	2.8×10^5	1.7×10^5	−40	–	–	C, A
Fungicide	Chlorothalonil	4.7×10^5	3.4×10^5	−28	–	–	C
Fungicide	Iprodione	2.6×10^5	1.3×10^5	−51	-9.8×10^3	0.69	C
Fungicide	Mancozeb	2.6×10^5	2.1×10^5	−20	–	–	C, A
Fungicide	Maneb	5.2×10^5	2.9×10^4	−45	–	–	C, A
Fungicide	Myclobutanil	7.3×10^4	2.8×10^4	−61	–	–	R
Fungicide	*Propamocarb HCl*	0	4.8×10^4	*(new)*	–	–	N
Fungicide	Thiophanate methyl	6.0×10^4	4.2×10^4	−30	–	–	R
Herbicide	2,4-D	3.3×10^5	2.6×10^5	−21	–	–	A
Herbicide	Acephate	1.8×10^5	6.0×10^4	−67	-8.7×10^3	0.88	N
Herbicide	Atrazine	2.0×10^4	1.2×10^4	−41	–	–	W
Herbicide	Bromacil	6.5×10^4	2.9×10^4	−56	–	–	W
Herbicide	Bromoxynil	5.7×10^4	3.8×10^4	−34	-2.0×10^3	0.55	R
Herbicide	Cacodylic acid	2.8×10^4	6.9	−100	-1.8×10^3	0.70	C
Herbicide	Cyanazine	2.6×10^5	0	−100	-1.8×10^4	0.74	R
Herbicide	Diuron	5.3×10^5	2.9×10^5	−45	–	–	C, W
Herbicide	EPTC	3.3×10^5	5.4×10^4	−83	-1.9×10^4	0.87	R, N
Herbicide	Molinate	6.8×10^5	3.6×10^3	−99	-4.7×10^4	0.96	R, N
Herbicide	Norflurazon	7.4×10^4	2.2×10^4	−70	–	–	W
Herbicide	Oryzalin	3.1×10^5	2.6×10^5	−15	–	–	C
Herbicide	Propyzamide	5.3×10^4	3.5×10^4	−35	–	–	C

Table 7.1 (continued)

Agricultural use	Compound[b]	Annual average applications, kg			Linear regressions, 1993[c]–2010, if $R^2>0.50$		Risk groups[b]
		1993–1995	2008–2010	% change	Slope, kg/yr	R^2	
Herbicide	Simazine	4.3×10^5	1.9×10^5	−57	-1.5×10^4	0.87	W
Herbicide	Thiobencarb	1.9×10^5	1.2×10^5	−36	–	–	N
Herbicide	Trifluralin	6.3×10^5	2.5×10^5	−60	–	–	A
Insecticide	*Bensulide*	2.9×10^4	1.1×10^5	*+286*	5.6×10^3	0.76	N
Insecticide	Carbaryl	3.8×10^5	5.6×10^4	−85	-2.3×10^4	0.85	R, C, N, A
Insecticide	Chlorpyrifos	1.4×10^6	5.9×10^5	−57	-5.2×10^4	0.75	N
Insecticide	Diazinon	6.2×10^5	7.9×10^4	−87	-3.6×10^4	0.94	N
Insecticide	Dimethoate	2.9×10^5	1.1×10^5	−61	-1.1×10^4	0.84	N
Insecticide	Endosulfan	1.6×10^5	2.1×10^4	−87	-8.6×10^3	0.79	A
Insecticide	Malathion	3.5×10^5	2.4×10^5	−33	-9.0×10^3	0.66	N
Insecticide	Methamidophos	1.8×10^5	7.8×10^3	−96	-1.1×10^4	0.71	N
Insecticide	Methidathion	1.7×10^5	2.2×10^4	−87	-1.0×10^4	0.80	N, A
Insecticide	Methomyl	3.3×10^5	1.1×10^5	−68	-1.7×10^4	0.81	N
Insecticide	Naled	2.1×10^5	7.7×10^4	−63	–	–	N
Insecticide	Oxydemeton-methyl	5.5×10^4	3.8×10^4	−31	–	–	R, N
Insecticide	Phosmet	1.1×10^5	8.9×10^4	−16	–	–	N
Insecticide	Propargite	8.3×10^5	1.6×10^5	−81	-4.7×10^4	0.93	R, C
Insecticide/nematicide	Aldicarb	1.3×10^5	2.6×10^4	−79	-9.7×10^3	0.51	N
Insecticide/nematicide	Carbofuran	1.2×10^5	3.9×10^3	−97	-8.7×10^3	0.87	N
Insecticide/nematicide	*Oxamyl*	3.2×10^4	4.0×10^4	*+25*	–	–	N
Plant growth regulator	Ethephon	4.3×10^5	1.3×10^5	−69	-1.9×10^4	0.83	N

[a] Data are from the California Department of Pesticide Regulation's (DPR) http://www.cdpr.ca.gov/docs/pur/purmain.htm. Pesticide Use Reports. Only compounds of regulatory interest that were applied in a total quantity greater than 10,000 kg in either 1993 or 2010 are included. Compounds in which the quantity is greater (>110 %) in the 2008–2010 annual average than in the 1993–1995 annual average are highlighted in italic

[b] *R,* listed in California state Proposition 65 (CP65) as known to have reproductive toxicity; *C,* listed as either a U.S. EPA B2 carcinogen or in the CP65 as causing cancer; *N,* organophosphate and carbamates that are cholinesterase-inhibitors, and targeted by the U.S. Food Quality Protection Act; *W,* listed in the California DPR groundwater protection list, part a; *A,* listed as a California DPR's toxic air contaminant

[c] Slopes and R^2 for metam potassium were based on 2000 (first use) to 2010

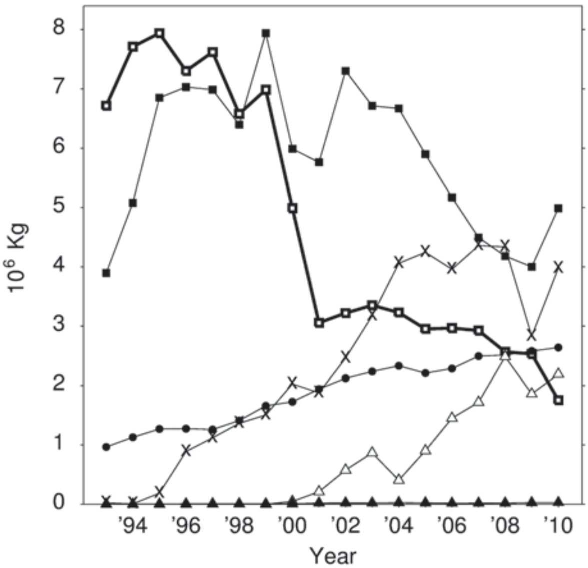

Fig. 7.1 Mass in millions of kg of agricultural fumigants used in California between 1993 and 2010. The data show the partial replacement of methyl bromide (□, thicker line) with 1,3-dichloropropene (X), chloropicrin (●), metam potassium (potassium n-methyldithiocarbamate) (Δ) and dazomet (▲); metam sodium (■) has been used throughout the period. Data are from the California Department of Pesticide Regulation's Pesticide Use Reports. http://www.cdpr.ca.gov/docs/pur/purmain.htm

7.1.3 An Example of Replacement of One Chemical with Others

The Methyl Bromide "Phase-Out" and its Replacements in California. Despite the extensive literature on substitution or reduction of chemical use with IPM, in practice, there are many more examples of replacement of one chemical for another. In Fig. 7.1, we show data for fumigants applied in California from 1993 to 2010. Because methyl bromide that is released into the atmosphere from fumigation ultimately decreases UV protection by the upper ozone layer, the Montreal Protocol and subsequent international agreements mandated the global phase-out of methyl bromide as an agricultural fumigant starting in the early 1990s (Grahl 1992). Many countries around the world have ceased its use (Schafer 1999). The U.S. phase-out strategy called for freezing the yearly amounts used from 1993 to 1998 at 1991 levels (~25,500 metric tons $= 2.5 \times 10^7$ kg for "total consumption", = production + imports − exports), a 25 % reduction from that baseline between 1999 and 2000, a 50 % reduction from baseline during 2001–2002, a 70 % reduction from baseline during 2003–2004, and a complete phase-out by 2005 except for allowable exemptions, such as the critical use exemptions that the Montreal Protocol Parties accept. The U.S. nominated critical use exemptions at 39 % of baseline in 2005 and was authorized at 37 %; the nominations and slightly lower authorizations have declined yearly, to a 12.7 % nomination in 2010, and a 1.7 % nomination in 2014. As shown in Fig. 7.1 and Table 7.1, methyl bromide use declined by 69 % during the 1993–2010 study period ($R^2 = 0.85$) . However, California is far from a phase-out with 1.8 million kg of methyl bromide applied in 2010. In addition, methyl bromide declines (slope $= -3.8 \times 10^5$ kg/year) have been accompanied by an increase in the use of four other fumigants as methyl bromide replacements: 1,3-dichloropropene (slope = 2.7×10^5 kg/year; $R^2 = 0.86$); metam potassium (slope = 2.3×10^5 kg/year starting with its registration in 2000; $R^2 = 0.88$); dazomet (slope = 2.3×10^5 kg/year; $R^2 = 0.76$;); and chloropicrin (slope = 1×10^5 kg/year; $R^2 = 0.96$). All of the alternatives have their own exposure toxicity risks and all fumigants generate toxic volatile organic compounds. Although metam sodium can be used as a methyl bromide replacement, overall, it had a modest (17 %) decline in use between the 1993–1995 and the 2008–2010 periods. We note that the mechanism of pesticidal activity of three methyl bromide replacements (metam sodium, metam potassium and dazomet) are similar in that they depend on the release of methyl-isothiocyanate (MITC) during breakdown. Methyl iodide (iodomethane) was registered briefly in California in 2010 as a methyl bromide replacement, but was then removed from the market by its manufacturer.

There are many contributing factors for both the continued use of methyl bromide and, to the extent that it has been replaced with other fumigants, its replacements. In California, many crops (e.g., strawberries, stone fruits, nuts, grapes, peppers, and carrots), strawberry plant nurseries and the ornamental industry rely on pre-plant fumigation of the soil to kill pathogens and nematodes. Indeed, the California Department of Food and Agriculture (CDFA) Nursery Stock Nematode Control Program requires that tree, strawberry and grapevine nurseries produce nematode-free crops, which is difficult to achieve without fumigants. At the same time, fumigant use is constrained by regulations of the U.S. Environmental Protection Agency and the California Department of Pesticide Regulation (DPR), which require buffer zones, township caps (generally the amount that can be applied in a 93 km^2 area), and low emissions in California's Air Quality Non-Attainment Areas. The majority of California's major agricultural areas have been declared as federal non-attainment areas and are subject to California regulations to reduce emissions from fumigant pesticides; these areas include the entire San Joaquin Valley, Ventura County, the South Coast and Southeast desert (which includes the Coachella Valley), and the Sacramento Metropolitan area (Goodell et al. 2011). Township caps are particularly limiting for applications of 1,3-dichloropropene (1,3-D), which is on California's Proposition 65 carcinogen list. Although the DPR suspended use of 1,3-D in 1990 when it was detected above air quality standards in Merced County, it allowed 1,3-D applications to begin again in 1994, subject to regulation. Carpenter et al. (2001) estimated that township caps would limit the permits for 1,3-D in 47 townships, particularly in the strawberry-producing counties of Monterey and Ventura. Consistent with these caps, the use of 1,3-D has been flat between 2004 and 2010 (slope = 0, $R^2 = 0.16$) (Fig. 7.1).

Methyl bromide has been the foundation of soil-borne pathogen, nematode and weed control in California strawberry fruit production fields for the past 50 years (Schneider et al. 2003; Wilhelm and Paulus 1980) . University of California (UC) researchers were instrumental in the research and development of agricultural fumigants. Initially, Wilhelm and Koch (1956) used chloropicrin to control the fungal pathogen *Verticillium dahliae* in strawberry. Then, methyl bromide was added because it augmented the fungicidal properties of chloropicrin and also controlled weeds (Wilhelm and Paulus 1980). Importantly, a combined application of methyl bromide + chloropicrin provides a poorly understood growth promotion to strawberry (Wilhelm and Paulus 1980; Larson and Shaw 1995) and annual plants (Duniway 2002). The most common speculation about this activity of methyl bromide + chloropicrin is that in addition to killing well-characterized pathogens it also kills a highly variable array of organisms that are either difficult to culture (Johnson et al. 1962) or that are non-lethal root 'nibblers.' However, growth promotion might occur via a nutritional mechanism (Millhouse and Munnecke 1979) or one that affects microbial and enzymatic functions in soil (Stromberger et al. 2005). Regardless, contemporary strawberry production has been developed with methyl bromide fumigation. In California, strawberry fruit production increased from 38 metric tonnes per ha in 1972 to 150 metric tonnes per ha in 2010. Particularly in the major south and central coastal production areas, strawberries are produced year after year with no rotation. While the yield increases occurred by optimizing cultivars and cropping practices, "conventional" fields were all pre-plant methyl bromide/chloropicrin-fumigated.

Historically and currently, most of the methyl bromide fumigation in the U.S. is in soil for strawberry fruit production. In 2011, California growers produced 2.57 billion pounds (1.17 billion kg) of strawberries, accounting for 89% (USDA 2011) of U.S. production (California Department of Food and Agriculture 2013). The U.S. Department of Agriculture (USDA) lists the following as registered methyl bromide alternatives: 1,3-D; chloropicrin; dazomet; dimethyl disulfide; metam sodium; the herbicide terbacil (with minor use in California); 1,3-D + chloropicrin; 1,3-D + chloropicrin + metam sodium; and metam sodium + chloropicrin (http://www.epa.gov/ozone/mbr/alts.html#***). Critical use exemptions are allowed when "(i) … lack of availability of methyl bromide … would result in a significant market disruption; and (ii) there are no technically and economically feasible alternatives or substitutes available to the user that are acceptable from the standpoint of environment and public health and are suitable to the crops and circumstances of the nomination." The 2014 U.S. critical use nomination exemption includes 415,607 kg methyl bromide (94 % of the entire U.S. nomination) for fumigation of soil for strawberry fruit production in California. The nomination was based on an application from the California Strawberry Commission, a private commodity group that works closely with UC researchers. The nomination argues for methyl bromide treatment of 16 % of the strawberry fruit acreage for the following reasons: the 1,3-D caps limit the availability of that fumigant; iodomethane may not be accepted by consumers (and indeed is not available as of 2012); and two currently relatively minor pathogens, *Macrophomina phaseolina* and *Fusarium oxysporum* (Koike 2008; Koike et al. 2009) are not adequately controlled by the methyl bromide alternatives. In the nomination, the U.S. is focused on maintaining the yields and the profit margins achieved in a methyl bromide-system.

Interestingly, in contrast to predictions (Goodhue et al. 2005), the years of declining methyl bromide use have been years of increasing California strawberry yields, acreage, exports, revenue and market share (Mayfield and Norman 2012). Gareau and DuPuis (2009) argue that U.S.-backed policies of granting Montreal Protocol exemptions based on claimed economic losses to California growers is incompatible with meeting public health goals for protection of the ozone layer in the upper atmosphere. We contend that using methyl bromide as the standard—with its attendant control of soil-borne pathogens, weeds, and nematodes, and its plant growth promotion—reduces IPM into an Integrated Pesticide Management system that will ultimately inhibit the development of a fully sustainable agriculture that considers all of the environmental and health externalities.

Several fumigation and non-fumigation alternatives for California strawberries are in the testing stage. There have been advancements in fumigation tarps, which allow lower application rates (Fennimore and Ajwa 2011). Two non-fumigation methods are currently being tested: (1) steam, which is currently energy intensive but may become more efficient after further equipment modifications (Samtani et al. 2012); and (2) "anaerobic soil disinfestation," which has combined solarization (Morgan et al. 1991) with the addition of organic amendments. The combination of carbon source addition, soil saturation, and a plastic tarp helps generate higher temperatures, and generates temporary anaerobiosis and fungitoxic compounds. The anaerobic disinfestation of strawberry soil reduces pathogens but not weeds (Daugovish et al. 2011) and results in strawberry yields similar to fumigated treatments (Shennan et al. 2011). While rotation is the classic method to control plant disease and is used in organic strawberry production, because land costs are high and operating profit margins on strawberries are estimated currently at 17 % (http://www.epa.gov/ozone/mbr/CUN2014/2014CUNStrawberryFruit.pdf), conventional strawberry growers in California will not adopt rotation at this time.

7.1.4 Examples of Increased Use of Compounds that Have or Might Have Adverse Agricultural or Health Consequences

During the 50-year history of IPM (Stern et al. 1959), California agriculture has intensified with more monoculture, less rotation and larger acreages of plantings—factors that tend to increase pesticide use. As indicated above, many of the older materials of regulatory concern (Table 7.1) have decreased in use. For example, use of the organophosphate chlorpyrifos, which is targeted by the Food Quality Protection Act, declined between the 1993–1995 and the 2008–2010 periods by 57 % ($R^2=0.75$). Nonetheless, even though chlorpyrifos is an important water pollutant in California (Bailey et al. 2000), with use at 5.9×10^5 kg/year during the 2008–2010 period, it remains a highly used insecticide and miticide particularly on almonds, oranges, walnuts, alfalfa, wine grapes, and broccoli. Human health concerns about chloropyrifos remain (Rauh et al. 2012). Using a combination of PUR data, and historical amphibian survey data, Davidson (2004) found a significant association between applications of cholinesterase inhibiting pesticides (mostly organophosphates and carbamates) and downwind declines in multiple frog species in California.

Although chloropyrifos and the other organophosphate and carbamates have declined in use, they have been largely replaced by newer materials, which are often toxic to pests at lower masses, albeit with less mammalian toxicity. For example, neonicotinoid use has increased between 1993 and 2010 (Fig. 7.2), and may be involved in colony collapse disorder of honeybees (Henry et al. 2012; Isawa et al.

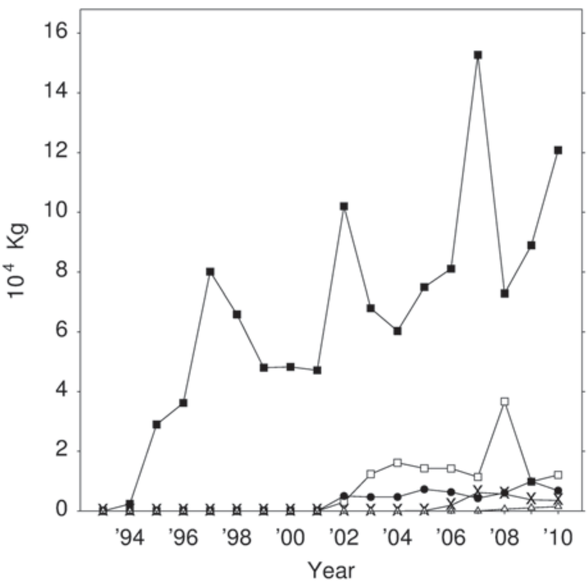

Fig. 7.2 Mass in 10^4 kg of neonicotinoids, a new class of insecticides and miticides, that were applied in California between 1993 and 2010, based on the California Department of Pesticide Regulation's Pesticide Use Reports <http://www.cdpr.ca.gov/docs/pur/purmain.htm>. The neonicotinoids have been implicated as a possible cause of colony collapse disorder in bees and include imidacloprid (■), acetamiprid (□), thiamethoxam (●), dinotefuran (X), and clothianidin (Δ)

2004; Schneider et al. 2012; Whitehorn et al. 2012). Honeybees are highly sensitive to numerous newer insecticides that have low mammalian toxicity (Casida 2012). In addition to neonicotioids such as imidacloprid (Isawa et al. 2004), examples of insecticides with high honeybee toxicity include the reduced-risk spinosad (LD_{50} = 3 ng/g) and the pyrethroid deltamethrin (LD_{50} = 23 ng/g) (Casida 2012).

7.1.4.1 Pesticide Resistance

The herbicide glyphosate has been the most-used pesticidal active ingredient in U.S. agriculture since 2001 (Grube et al. 2011). While it is not the dominant pesticide in California, glyphosate is currently the most extensively used herbicide in California by weight. Pesticide Use Report data on glyphosate use in California (Fig. 7.3) indicates an average increase of 1×10^5 kg/year ($R^2 = 0.89$) for the 1993–2010 period (Fig. 7.3). In contrast to the 17 herbicides of regulatory concern listed in Table 7.1, glyphosate is relatively free of environmental and health concerns. Although as discussed later, since California has relatively few genetically modified crops, the increase in glyphosate use is due to its low cost (it was off-patent in 2000), efficacy, and safety (Duke and Powles 2008). Two apparent consequences of increased glyphosate use are changes in the distribution of weed species and the emergence of herbicide resistance. In California, glyphosate-resistant strains have emerged in the following species: Italian ryegrass (*Lolium multiflorum*) (Jasieniuk et al. 2008); rigid ryegrass (*Lolium rigidum*); hairy fleabane (*Conyza bonariensis*); feral, genetically-modified glyphosate-resistant canola (Munier et al. 2012); jungle rice (*Echinochloa colona)* (Alarcón-Reverte et al. 2013); Palmer amaranth (*Amaranthus palmeri*); and horseweed (*Conyza bonariensis*) (Hanson et al. 2009). In the case of

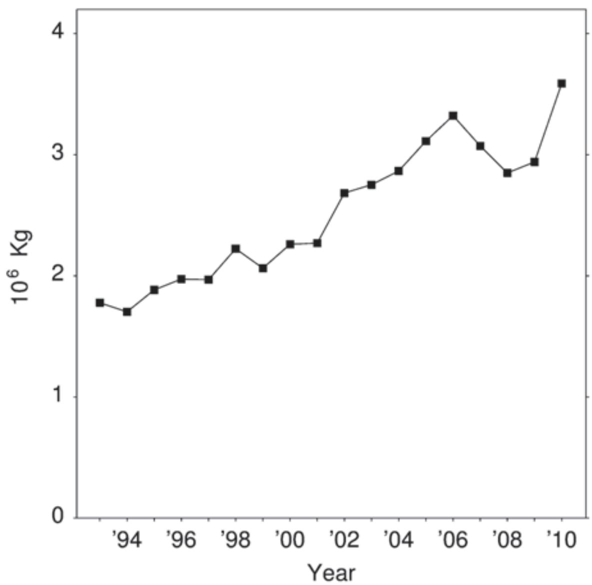

Fig. 7.3 Mass in millions kg of the herbicide glyphosate that was applied in California between 1993 and 2010, based on from the California Department of Pesticide Regulation's Pesticide Use Reports. <http://www.cdpr.ca.gov/docs/pur/purmain.htm>

glyphosate-resistant horseweed, the resistant strain has a greater impact on young grapevine growth than the glyphosate-susceptible strain (Alcorta et al. 2011). The International Survey of Herbicide Resistant Weeds lists 26 herbicide-resistant biotypes in California (http://www.weedscience.org).

Insecticide resistance (Zalom et al. 2005) and fungicide resistance (McGrath 2012) are also critical issues in California agriculture. UC IPM-recommended strategies for stalling fungicide resistance are based on recommendations of the Fungicide Resistance Action Committee (http://www.frac.info), which focuses on resistance avoidance by using products which vary in the fungal target site. Consequently, the UC IPM recommendations primarily involve alternation of fungicides with different modes of action. There are two ramifications of this recommendation. First, it tends to continue use of compounds of greatest regulatory concern, partly because these compounds often have multiple-sites of action and consequently are less likely to select for resistance. Second, the recommendations do not provide a strategy for avoiding selection of multi-drug resistant strains, which often have a mutation in a cellular pump that exports multiple drugs (Kretschmer et al. 2009).

7.1.4.2 Emergence of Secondary Pests After Pesticide Applications

There are many cases in which use of a pesticidal product ultimately results in a previously secondary pest becoming a primary problem (Kennedy 2008). In California in 1889, the vedalia beetle, *Rodolia cardinalis*, was imported and successfully introduced into citrus orchards as a biocontrol for the cottony cushion scale, *Icerya purchasi*, (Mills and Daane 2005). However, use of compounds in the newer classes of insect growth regulators, neonicotinoids, and pyrethroids can kill the vedalia beetle, which led to scale outbreaks (Grafton-Cardwell and Gu 2003).

7.1.4.3 Additional Comments on Pesticide Externalities

Externalities (economic impacts from pesticide use that are not paid for by either the manufacturer or the grower) are often complex issues that are difficult to assess and quantify (Devine and Furlong 2007; Leach and Mumford 2008; Waterfield and Zilberman 2012). Pimentel (2009) estimates that \$ 10 billion/year in pesticide control saves approximately \$ 40 billion in U.S. crops, but generates \$ 9 billion in environmental and public health externalities with the following major annual costs: ground water contamination, \$ 2 billion; public health, \$ 1.1 billion; pesticide resistance in pests, \$ 1.5 billion; crop losses caused by pesticides, \$ 1.1 billion; and bird losses due to pesticides, \$ 2.2 billion. We provide a few examples of toxicities from relatively low levels of contamination on aquacultural and agricultural productivity. Some insecticides, herbicides and fungicides are extremely toxic to fish, such as deltamethrin ($LC_{50} \approx 1$ ppb), the herbicide trifluralin ($LC_{50} = 88$ ppb), and the fungicide captan ($LC_{50} \leq 0.3$ ppm) (Casida 2012) . Fox et al. (2007) found that residues of the organophosphate insecticide methyl parathion inhibited nitrogen-fixing bacteria and estimated that alfalfa yields could be reduced by one-third by residues. Although the organically-acceptable copper is considered a safe fungicide and bactericide because it has low mammalian toxicity, it accumulates in topsoil and is toxic to beneficial microorganisms and sensitive crops (Epstein and Bassein 2001). Based on the individual PUR records, they estimated that during the 6-year study period from 1993 to 1998, a walnut orchard with the mean copper application would acquire 28 mg per kg dry weight soil in the upper 15 cm of soil and that 125 km^2 of walnut orchards (17 % of the area planted with walnuts in California) would acquire 50 mg copper per kg dry weight in the upper 15 cm of soil in the 6-year period. Although several soil factors affect toxicity, the following mg copper per kg soil are considered inhibitory to the following: beneficial mycorrhizal fungi, 34; soil respiration, 50; earthworms, 80–110; and copper-sensitive crops, 100–150. Consequently, the externalities of pesticides may be underestimated.

7.2 IPM and Pesticide Use

7.2.1 An Overview of IPM Infrastructure in California

The University of California Statewide (UC) IPM program defines IPM as "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." (http://www.ipm.ucdavis.edu/GENERAL/ipmdefinition.html).

Historically, the UC has been a leader in IPM research, particularly in facilitating the development of predatory insect populations that naturally control insect pests (Stern et al. 1959). IPM has been broadly embraced, particularly in California, as a strategy for both optimizing and minimizing pesticide use (Brewer and Goodell 2012). However, a U.S. Government Accounting Office (GAO) report stated that "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" (US GAO 2001). Regardless, in practice, IPM often degenerates into "Integrated Pesticide Management" (Ehler 2006), with IPM providing a rationalization for pesticide use (Zalucki et al. 2009).

The most influential program supporting IPM adoption in California is institutionally housed at the UC Statewide Integrated Pest Management Program. The Statewide IPM Program was essentially formed by the state legislature in 1979 with the appropriation of funds (Zalom 1996). The stated goals of the program are to: "reduce the pesticide load in the environment; increase the predictability and thereby the effectiveness of pest control techniques; develop pest control programs that are economically, environmentally and socially acceptable; marshal agencies and disciplines into integrated pest management program; and increase the utilization of natural pest controls."

Currently the program maintains a web site (http://www.ipm.ucdavis.edu/) with extensive information on the following main topics: agricultural, urban, and wildland pests and their control; information on exotic and invasive pests; annotated image galleries of weeds and beneficial insects; degree-day calculators and links to weather data; links to pest and plant models; and links to pesticide information. UC IPM produces comprehensive print and digital pesticide application information and IPM manuals for growers and pest control advisors. Information for growers, pest management professionals and pesticide applicators is also available through workshops, events and online training programs. The journal *California Agriculture* (http://californiaagriculture.ucanr.org/) has peer-reviewed articles, many of which focus on IPM (Brodt et al. 2007; Epstein et al. 2000).

The broader University of California Division of Agricultural and Natural Resources (ANR) has academic researchers at the UC Davis in the College of Agricultural and Environmental Sciences and the School of Veterinary Medicine, the UC Riverside College of Natural and Agricultural Sciences, and the UC Berkeley College of Natural Resources. These departments often have UC Co-operative Extension specialists, some of whom focus on IPM to varying extents. ANR also has nine Research and Extension Centers throughout the state, primarily in agricultural areas. ANR also has 57 local offices with UC Co-operative Extension farm advisors, many of whom perform at least some IPM research and/or outreach; about 11, all with Ph.D. or M.S. degrees, have specific IPM responsibilities. Mullen et al.

(2003) estimated that the UC spent $ 26.2 million in 1997 (in year 2000 $) on pest management, amounting to about 35 % of its agricultural research budget.

On the state level, the California Department of Pesticide Regulation (DPR) also promotes IPM (Barnes et al. 2012). Under California law, pest control advisors (PCAs) must be licensed by DPR. Licenses require passing an exam on IPM, and taking continuing education on IPM. UC ANR's *IPM in Practice: Principles and Methods of Integrated Pest Management*, 2nd ed. is the official study guide for the PCA exam (www.ucanr.edu/IPMpractice). In practice, many but not all pest management professionals sell pesticides and have an economic conflict of interest between pesticide sales and promoting minimum use. However, although Brodt et al. (2007) found that independent PCAs on cotton in California in 2000 communicated more with growers than their product supplier-counterparts, most of their on-the-ground treatment recommendations were similar. Growers and pesticide companies both interact with the broader UC ANR community in multiple ways. The California Marketing Act of 1937 enabled growers to form commodity groups that can collect revenue based on sales of that commodity. The commodity boards sponsor both marketing and research; commodity grants to UC ANR are generally exempt from overhead charges. Comparative pesticide efficacy trials are frequently conducted by UC ANR personnel.

7.2.2 IPM and Pesticide Use

California and U.S. agriculture are pesticide-dependent. In 2007, the U.S. spent 32 % of the total world's expenditures for pesticides, with 38 % of world's expenditures on herbicides (which includes plant growth regulators), 39 % of world's expenditures on insecticides/miticides, 15 % of world expenditures on fungicides, and 25 % of world expenditures on "other" pesticides (which includes nematicides, fumigants, sulfur, petroleum oils and some other products) (Grube et al. 2011). Agriculture accounted for 72 % for the U.S. expenditures in herbicides, 46 % of the insecticides/miticides, 78 % of the fungicides and 67 % of the "other pesticides." (Grube et al. 2011). Use of agricultural fungicides and bactericides in California from 1993 to 2000 is discussed in Epstein and Bassein (2003).

While, theoretically, genetic modification could substantially reduce broadcast applications of insecticides and fungicides into the environment, in practice, it has had little effect in California. As of 2012, there were relatively few genetically modified plants in commercial California agriculture. Of the three crops that dominate the U.S. genetically modified market (soybeans, corn and cotton), in 2011, California produced less than 0.04 % of all the soybeans produced in the U.S., 0.2 % of the corn, and 8.6 % of the cotton (http://www.usda.gov/nass/PUBS/TODAYRPT/crop0912.pdf). However, in 2011, 41 % of California's cotton was American Pima, which has historically been difficult to genetically modify. Of the upland cotton, between 2000 and 2010 in California, the percentage that was herbicide-tolerant increased from 21 to 64 %. Herbicide-tolerance simplifies weed management by allowing greater flexibility in when herbicides can be applied, and, particularly in less-till situations, can ultimately result in less fossil fuel use for plowing, and less soil erosion from bare-fields. However, herbicide-tolerance has not reduced herbicide use in the U.S. (Benbrook 2012) and seems unlikely to do so in the future. In contrast to herbicide tolerance, the percentage of cotton that produced the *Bacillus thuringiensis* (Bt) toxin (with or without herbicide tolerance) only increased from 7 to 27 % (http://www.ers.udsa.gov). Factors that affect the relative lack of adoption of Bt-cotton include the following: the higher cost of genetically modified seed; the lack of economically important lepidopteran pests in some areas of the San Joaquin Valley; the current efficacious control of the (Bt-sensitive) pink bollworm (*Pectinophora gossypiella*) by a California Department of Food and Agriculture and grower IPM program that includes monitoring, sterile release, crop destruction and occasional pheromone treatments; and, in some parts of southern California, lepidopteran pressure that is so high that insecticidal applications have to be made regardless of the Bt toxin in the genetically modified cotton. In those areas in which Bt-cotton is grown, it may have benefits in reduction of insecticide applications (Epstein and Bassein 2003). The Bt toxin in cotton and corn in the U.S. has reduced insecticide use (Benbrook 2012).

In an economic analysis of pesticide use reduction by IPM programs in California, Mullen et al. (2005) concluded that IPM programs had saved over $ 1 billion in pesticide costs for almonds, cotton, oranges and processing tomatoes since 1970. Their "first approximation" was that a benefit-cost ratio for investments in agricultural research and in pest management were both 6:1, although in specific case studies in pest management in almond, cotton, orange and processing tomato, the benefit:cost ratios were estimated as 5.5:1, 4.4:1, 0.4:1, and 2.8:1 (Mullen et al. 2003).

IPM can reduce pesticide use and costs without compromising yield in some circumstances (for examples, see Hendricks 1995; Flint et al. 1993; Pretty 2005; Swezey et al. 2007). Trumble and colleagues (Trumble et al. 1997; Reitz et al. 1999) reduced a "calendar application" program of nine applications of the organophosphate methomyl and the pyrethroid permethrin per season on celery (*Apium graveolens*) in California to a program with scouting and application of "biorational" insecticides only when pests were at threshold levels. Yields were similar in the chemical and IPM treatments, and greater than in the untreated controls, but grower costs were $ 250/ha less in the IPM than in the chemically-intensive program.

California does have IPM success stories. Graebner et al. (1984) describe a voluntary collective of citrus growers in the Fillmore, California area from 1922 to 2003 in a grower cooperative that operated an insectary that produced more than 20 species of beneficial insects and mites. In addition to supplying as many as a half-million predatory and parasitic insects per day, for a maximum of 250 growers farming over 3,000 ha, the growers agreed to adhere to a collective strategy for pest control. Initially, the growers replaced the use of cyanide gas, and continued to use biocontrol instead of chemicals. According to the Los Angeles Times, "In recent years, only about 2 % of the acreage in the district has required chemical treatment, according to district officials." (http://articles.latimes.com/2003/aug/10/local/me-insect10). As a result of the economic downturn in Valencia oranges and the replacement of citrus orchards with more profitable crops, the Fillmore insectary was closed in 2003 after more than 80 years of successful biocontrol.

Fig. 7.4 An IPM success story: pear IPM in California, USA. Codling moths (*Cydia pomonella)* are a major pest on pears. **a**) A mature codling moth larva, typically 13–19 mm in length. **b**) A male and female codling moth adult, typically 8 mm long. **c**) The codling moth damage, just around the calyx of a pear and internally, is caused by larval feeding and excrement; some mechanical injury is also present on the pear. **d**) University of California North Coast Area IPM Advisor Lucia Varela instructs agricultural workers about identification of insects and their damage on pears. **e**) UCCE staff member Jim Benson hanging an experimental pheromone "puffer" dispenser used in an area-wide codling moth mating disruption project in Lake County, California. The success of the pear IPM program to switch growers from an organophosphate insecticide-dependent control to a more sustainable IPM control program that includes use of pheromones for mating disruption has depended upon multiple factors: publically-funded research and extension by the University of California; the implementation of an area-wide program so that treated orchards were not bordered by untreated orchards; grower participation and collaboration; and careful attention to the development of cost-effective pheromone technology that can be distributed efficiently in orchards with relatively low labor costs. Photos are courtesy of the University of California Statewide IPM Program

Weddle et al. (2009) describe IPM programs to control insects in pears in California from the 1960s to the present. As in the rest of the United States, insect control in the 1960s was highly dependent on chlorinated hydrocarbons, organophosphates and carbamates. As a result of UC-IPM programs and grower alliances (Varela and Elkins 2008) current arthropod IPM in California pears can be classified as efficacious, relatively low input, and biologically intensive. Typical current practices in California pears include the following: regular use of a mating disruption pheromone for codling moth (Fig. 7.4); occasional use of insect growth regulators for leafrollers and codling moth; lime sulfur, particularly for mite control in organic orchards; the natural product abamectin for mite and psylla control; and mineral oil for suppression of psylla, mites and codling moth. In Sect. 7.3.1, we summarize data from the Pesticide Use Reports about phasing out organophosphates on almond and stone fruit orchards during the winter rainy season, the period when pesticides most readily are transported by run-off into surface water.

Integrated pest control is challenged by numerous factors that do not tend to reduce pesticide use or risk: (1) in the U.S. many consumers demand cosmetically perfect fresh fruits and vegetables (Castle et al. 2009); (2) there have been repeated introductions of invasive species unaccompanied by their natural enemies; (3) growers often treat so that they will be able to sell to a wide range of potential export markets, each of which may have different standards (Castle et al. 2009); (4) standards of "best management practice" for farm managers and recommendations of pest control advisors may focus on protection from worst-case scenarios; and (5) IPM strategies generally have to be justified to individual growers based on economic arguments, while the benefits of the IPM often require regional participation, and the benefits, at least partly, accrue to the broader farming community and the public (Brewer and Goodell 2012). While some studies show that, IPM reduces pesticide use in the U.S. (e.g., Mullen et al. 2005), others show the opposite (e.g., Maupin and Norton 2010). As the latter study points out, comparisons between different studies on this point are difficult due to differences in definitions of "IPM" and the multitude of external factors which influence pesticide applications by individuals. Nonetheless, Maupin and Norton (2010) concluded that, on average, IPM strategies in the U.S. from 1996 to 2005 led to slightly increased pesticide spending and kilograms of active ingredient per hectare.

Using literature reviews and telephone interviews, Epstein sought examples in which a researcher thought that an IPM program in California during the 1990s had resulted in reduced use of pesticides and that the PUR data supported the contention (Epstein and Bassein 2003). There were a few examples with insecticides (Epstein et al. 2000; Epstein et al. 2001), primarily with organophosphates that are mentioned in this chapter. Epstein and Bassein (2003) examined two pathosystems in which anecdotal and/or survey data supported a reduction in fungicide use but the PUR data indicated there had been relatively consistent fungicide use.. Diseases on grapevine provide useful case studies of pathogen management in California because there are a large number of growers and acreage; in 1995, there were 6,181 vineyards and a total of 1,645 and 1,343 km^2 of wine and non-wine grapes, respectively. In addition, one can make reasonable predictions on why applications were made, based on the active ingredient and the time of applications. The assumption is often made that participating growers in an IPM program are representative of the grower community and, specifically, as people that are interested in IPM, they are not more pesticide-intensive than the rest of the grower community. However, comparisons of the distribution of farm size of UC IPM grapevine survey respondents and PUR "acre planted" per grower ID suggested that the participants in UC IPM programs are not random samples. Similarly, comparisons of PUR and survey data suggested that IPM program participants may be more pesticide-intensive than the grower community. Theoretically, replacement of a historically-used "one size fits all" "calendar spray" pesticide program with an "environmentally driven" program could reduce pesticide use, particularly in years with lower disease pressure. However, this assumes a relative homogeneity of grower programs with the majority of growers currently using the higher-frequency "calendar spray" program. In addition, there is the assumption that if there are growers that currently use less than recommended pesticide dosage by an environmentally-driven program, that they would not increase their use. The study period from 1993 to 2000 included multiple years before the introduction of an environmentally-driven program that extended the recommended interval between applications when temperatures were sub-optimal for the pathogen that causes powdery mildew (Gubler et al. 1999). The analysis of PUR data indicated that while there were subset of growers who appear to use the calendar spray model, and consequently, could reduce their fungicide use, the majority of growers appeared to have a schedule that was less than would be recommended by the environmentally-driven model. While these growers might conceivably have better disease control if they adopted the environmentally-driven model, if all growers adopted the environmentally-driven model, there would be a net increase of fungicide use in California grapevines. Consequently, the data suggested that widespread adoption of the IPM program would increase fungicide use (Epstein and Bassein 2003).

The second example (Epstein and Bassein 2003) involves control of Botrytis bunch rot in grapevines with either fungicides or a non-chemical cultural practice of selective leaf removal; leaf removal increases air flow, decreases the hours that berries are wet, and consequently makes the environment less conducive for fungal infection. Leaf removal was implemented in the higher value, wine grape-growing areas on the California coast in the 1990s largely because it improves fruit quality by increasing sunlight on the berries. Based on anecdotal reports, the media stated that growers' adoption of leaf removal resulted in decreased fungicide use. However, analysis of PUR records indicated that the use of fungicides used to control bunch rot on wine grapes on the coast vacillated yearly but was overall stable between 1992 and 1997, the time period during which both UC IPM survey data and anecdotal reports indicated that leaf removal was increasing. Overall, the data suggest that growers' control programs are more heterogeneous than often implied in the pest control literature, and that while some growers reduced their chemical control programs, others increased their control programs. In section 7.3.2, we discuss a third example in which growers added the biological control agent *Pseudomonas fluorescens* to a chemical control program instead of replacing the chemical control.

7.3 Two Case Studies in IPM in California based on the Pesticide Use Reports

7.3.1 The Reduction of Organophosphates (OP) in Dormant Almond and Stone Fruit Orchards during the California Rainy Season

Pesticide contamination of surface water and groundwater in California, and in the U.S., are well documented externalities of pesticide use (Gilliom et al. 2006; Starner and Goh 2012). In the early 1970s, UC entomologists introduced the practice of

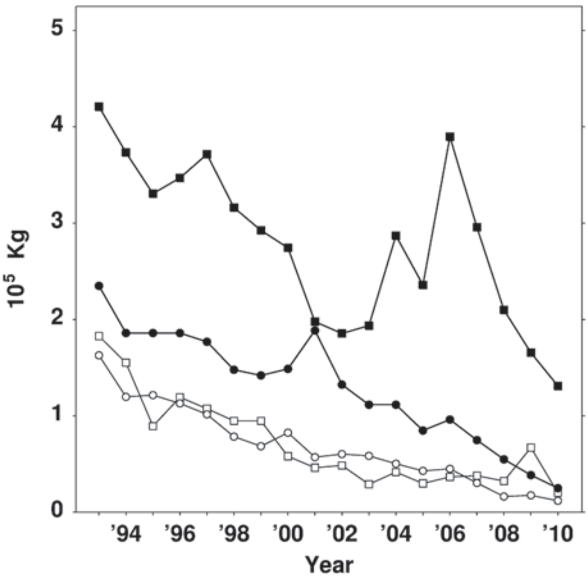

Fig. 7.5 Mass in 10^5 kg of organophosphates (OP) applied in California orchards between 1993 and 2010 on almond and stone fruit (peaches, nectarines, prune, & plum) orchards either during the dormant season (10 December of the previous year to 20 March of the indicated year) or annually. Total annual on almond (■ thicker line), dormant-season on almond (□), total annual on stone fruits (● thicker line), dormant-season on stone fruit (○). OP include acephate, azinphos-methyl, bensulide, chlorpyrifos, ddvp, diazinon, dimethoate, disulfoton, ethephon, fenamiphos, malathion, methamidophos, methidathion, methyl parathion, naled, oxydemeton-methyl, phorate, phosmet, propetamphos, s, s,s-tributyl phosphorotrithioate, temephos, and tetrachlorvinphos

an OP insecticide application during the dormant season in almond orchards as an environmentally-preferred practice (Rice et al. 1972). Environmental advantages of a dormant-season vs. in-season OP application include the following: one dormant season application can replace multiple in-season applications; there are fewer adverse affects on beneficial arthropods during the dormant period, workers are less likely to be in the field at this time and consequently there is less human exposure to pesticides; and there is no exposure of fruit to potential residues. However, in California, the dormant season is also the rainy season, and when deciduous tree crops lack leaf cover, pesticides more readily run-off into surface water. Consequently, the resultant water pollution from dormant-season OP use on both almond and stone fruits has resulted in violations of the Federal Clean Water Act. During the 1990s, in response to food safety groups, regulatory agencies began to critically examine the health and environmental effects of OPs. The UC Statewide IPM program and the Biologically Integrated Orchard Systems (BIOS), a coalition of public and private groups, promoted the replacement of OPs on almonds during the rainy season with alternative practices. There was also a much smaller research and extension effort in stone fruits, which share many of the same pests with almonds. Figure 7.5 shows the mass of OPs applied between 1993 and 2010 during the rainy season and during the entire year on almonds and on stone fruit. The data show excellent progress in reduction of dormant season OPs during the rainy season on almond (slope = -7.4×10^3 kg/yr, $R^2 = 0.72$) and on stone fruit (nectarine, peach, plum, and prune) (slope = -7.5×10^3 kg/yr, $R^2 = 0.93$). The percentage of mass of OPs that were used in the dormant season versus annually decreased from 43 % in the 1993 to 1994 period to an average of 17 % in the 2003–2010 period in almond, and from 67 to 45 % in stone fruits. Using PUR records in a way that allowed reconstruction of individual grower practices between 1992 and 2000, Epstein and Bassein (2003) showed that the reductions in OPs in stone fruits were primarily due to replacement with pyrethroids. However, in almonds, in which there was a more sustained UC IPM education and extension program, more of the OP applications were replaced with either no treatment (presumably due to monitoring and a decision not to treat) or the use of a "sustainable" alternative: the biocontrol agent *Bacillus thuringiensis* at bloom time; or oil without an insecticide during the dormant season. Despite the decline in the dormant season OPs, almond growers had a spike in use of in-season OPs around 2006; this was probably due to: (1) increased pest pressure from the San Jose scale, the navel orangeworm, and ants; and (2) expectations of a good price (http://www.cdpr.ca.gov/docs/pur/pur06rep/06com.htm#trendscom). Almond prices went from $ 2/kg in 2001 up to $ 5.73/kg in 2005 and then down to $ 3.22 in 2008.

7.3.2 Microbial Biopesticides

The DPR requires reporting of applications of microbial biological control agents. There is a vast literature on application of microbes as biocontrol agents with multiple journals that focus on the topic, for example, *BioControl* (Springer), *Biological Control* (Elsevier), and *BioControl Science and Technology* (Taylor & Francis). Biocontrol has been a popular area of research within the USDA and the academic community for multiple reasons: microbial biocontrol is viewed as "environmentally friendly;" the application of biocontrol agents fits in with the "magic bullet" chemical paradigm of pathogen and pest control; commodity groups can use the lack of efficacy of a biocontrol agent as part of a rationale for a U.S. Sect. 18 emergency pesticide exemption; and microbial biocontrol agents are patentable (Saenz de Cabezon et al. 2010). Nonetheless, reproducible efficacy in the field has been problematic for many agents. *Bacillus thuringiensis*, the producer of *Bt*-toxin, has been uniquely successful in achieving widespread adoption in commercial agriculture, as is evident in aggregate data from 22 registered strains (Fig. 7.6a). During the 1993–2010 study period, the most popular strains have changed; genetically engineered *Bt* have been registered, but their use is limited, and they are not allowed in organic agriculture.

Besides *Bt*, 23 other microbial biological control products have been registered in California, and the most successful are shown in Figs. 7.6a and b; Figure 7.6b shows the eight (other than *Bt*) that were applied in the greatest quantity. The data show that new biocontrol agents are often tried by growers, but not

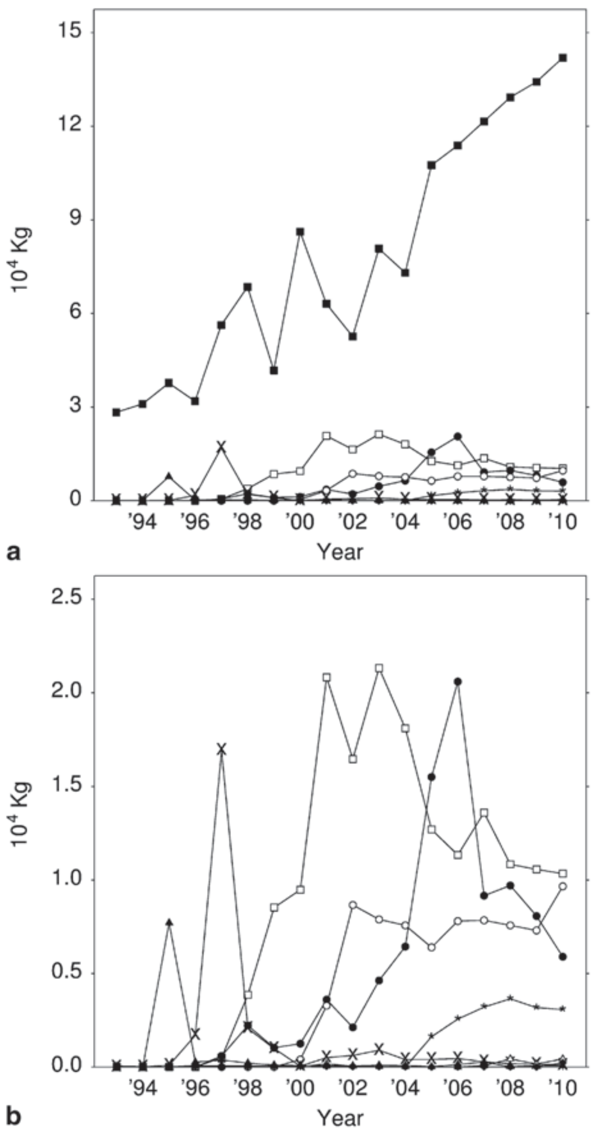

Fig. 7.6. Mass in 10^4 kg of the microbial biocontrol agents that were applied in California between 1993 and 2010, based on data from the California Department of Pesticide Regulation's Pesticide Use Reports <http://www.cdpr.ca.gov/docs/pur/purmain.htm>. Only those agents in which more than 500 kg was applied during the entire study period are included. The microbes listed here are *Bacillus thuringiensis* (■), *Myrothecium verrucaria* (□), *Bacillus sphaericus* (●), *Bacillus subtilis* (○), *Pseudomonas fluorescens* (X), *Bacillus pumilus* (*), *Agrobacterium radiobacter* (▲), *Gliocladium virens* (Δ),and *Trichoderma harzianum* (♦). **a**) All agents are included; use of *B. thuringiensis* (■) dwarfs all others. **b**) All of the indicated agents except *B. thuringiensis* are shown on a scale 1/6th that of **a**)

necessarily continued. In Fig. 7.6b, a peak of use occurred in 1995 for *Agrobacterium radiobacter* (▲), a bacterium isolated for crown gall control that is applied to roots before transplanting, but lacks the competitive ability to colonize and persist on roots. Use of *Pseudomonas fluorescens* (X) peaked in 1997. Although use of the nematocidal (and herbicidal) preparation of killed cells of the plant pathogenic fungus *Myrothecium verrucaria* with its fermentation products from axenic culture (□), was greater in 2001 through 2004, it has had more sustained use. The bacterium

Bacillus sphaericus (●) is formulated as a larvicide for aqueous applications for killing Diptera (flies, mosquitoes, midges, and gnats); and its use appears to have peaked in 2006.

The organic agricultural markets in California are expanding rapidly (Klonsky 2012), and this expansion is providing opportunities for use of the approved biopesticides. In the last 10 year period, organic production went from 0.5 % of California farmgate sales to its current 3 %. California produces two-thirds of the U.S. organic vegetables and over one-half of the organic fruit (Klonsky 2012). Some of the more recent products represented by the agents shown in Fig. 7.6 that have been marketed for organic agriculture and greenhouse production are from Agraquest, which was acquired by Bayer CropScience in 2012: a fungicide with *Bacillus subtilis* (○), and two fungicides with *Bacillus pumilus* (*). The two other biopesticides in Fig. 7.6b are *Trichoderma harzianum* (*) (BioWorks, Inc) and *Gliocladium virens* (Δ) (Certis). Several new commercial products have been registered and promoted since 2010.

Results of comparative tests of efficacy for microbial biocontrol agents for disease control are published by the American Phytopathological Society Plant Disease Management Reports (http://www.plantmanagementnetwork.org/pub/trial/pdmr/). Historically, except for *B. thuringiensis*, the microbial biocontrol market has been challenged by a lack of reliable, high efficacy in the field. California's largely hot, dry growing season reduces the survival of the biocontrol strains on aerial plant surfaces. Broadcast applications of microbes to soil rarely effect the composition of the soil microbial community. Pre-colonization of transplants or seeds with microbes that are adapted for survival and biocontrol activity on the particular plant host/soil environment could theoretically enable protection of crops from soil-borne pathogens. However, it remains to be demonstrated whether any of the newer agents will rise to the remarkable level of safety, efficacy, and multiple-target specificity of *B. thuringiensis.*

The biocontrol agent *P. fluorescens* A506 'Blight Ban' (Fig. 7.6, denoted by X) provides an interesting case study on IPM and biocontrol. In 1996 a UC research and extension program introduced *P. fluorescens* A506 for application in pear orchards as a substitute for antibiotics; the project was supported by the California growers' Pear Advisory Board. Three diseases of pears can be controlled with either the antibiotic streptomycin or with *P. fluorescens* A506: fire blight, caused by *Erwinia amylovora*; blossom blast, caused by ice-nucleating strains of *P. syringae*; and russetting, caused by various indole acetic acid producing bacteria. *P. fluorescens* can be used with or without antibiotics; indeed it can be tank mixed with streptomycin, which can even be used by organic growers. Epstein and Bassein (2003) used the PUR grower identification codes to reconstruct individual pear grower's pathogen control programs in order to determine whether growers that started to use a *P. fluorescens* used the agent instead of, or in addition to, chemical control. The 89 pear growers in the targeted IPM program that could be tracked over the 4 year period from 1995–1998 were selected for analysis. Growers with the most intensive antibiotic use in 1995 were more likely to use *P. fluorescens* in the later years ($P = 0.012$ by logistic regression). Of the growers in 1995 that used the median number or less, of applications of antibiotics, only 17 % used *P. fluorescens* in 1997 and 1998 whereas 60 % of the more intensive antibiotic users used *P. fluorescens*. Thus, the most intensive pesticide users were most likely to try the biocontrol alternative, but they did not decrease their antibiotic use. That is, the biocontrol was used most by those that wanted to intensify their disease control program.

7.4 Conclusions

1. According to the UC Statewide IPM program (http://www.ipm.ucdavis.edu/) "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, and modification of cultural practices. Pesticides are used only after monitoring indicates they are needed, and pest control materials are selected and applied in a manner that minimizes risks to humans, non-target organisms, and the environment." While the definition describes a laudable goal, common contemporary practice of pest management is highly pesticide-dependent and is prescribed based on factors such as comparative costs to the grower of the array of legal chemical choices, perceived efficacy of the products, and potential financial consequences to the grower from product use or lack of use. IPM could reduce pesticide use or risk if there were more incentives for growers to do so. As practiced, IPM is primarily a strategy for management of individual pests.
2. Overall, the UC IPM program has been highly successful in helping growers to decrease use of the organophosphate and carbamate pesticides targeted by the U.S. Food Quality Protection Act, partly by recommending products that have lower mammalian toxicity. Growers in California are willing to try new products.
3. The University of California (UC) and the UC Statewide IPM program has played a critical role in providing research and extension on IPM to California growers. Economic analyses have demonstrated that the research and extension have been a good investment for both the growers and the public. However, more, and not less, public funding is needed to assure that California agriculture in the twenty-first century promotes both truly integrated pest management and sustainable agriculture. Goals for achieving IPM need to be better integrated with goals for sustainability including: maintenance of crop biodiversity; the inclusion of diverse genetic resistance to pests and pathogens in crops; the stoppage of the loss, contamination, and salinization of groundwater and soil; and achieving an energetically sustainable agriculture in which the total calories from the crops exceeds the energy applied as inputs.

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