Agricultural Pesticide Best Management Practices Report

A Final Report for the Central Valley Regional Water Quality Control Board

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1 Executive Summary

The objective of this report is to evaluate best management practices (BMPs) associated with the prevention or mitigation of water quality impacts generated by agricultural pesticide use in California. Five representative pesticides, diuron (herbicide), diazinon, chlorpyrifos, and malathion (three organophosphate insecticides), and bifenthrin (pyrethroid insecticide) were selected to represent three classes of pesticides associated with surface water quality threats: herbicides, organophosphate pesticides (OPs), and pyrethroids. The selected representative pesticides are commonly used in the Central Valley Pesticide Basin Plan Amendment Project Area.

This study focused on the best management practices (BMPs) of conservation tillage, application timing, cover crops, water treatments such as PAM and Landguard™, buffers, irrigation efficiency, and constructed wetlands, due to their effectiveness for reducing off-site movement of pesticides in runoff, either dissolved in the water column or adsorbed onto sediment. As **Figure 1-1** illustrates, buffers, water treatments and conservation tillage are the most effective of these methods for reducing off-site movement of pesticides (82% to 100% average reduction). Improving irrigation efficiency is also viewed as highly effective in reducing pesticide runoff; however assessments in the literature were qualitative rather than quantitative measures. Constructed wetlands and tailwater return systems showed strong potential (71% average reduction), but exhibited a wider variation in results than the other BMPs. Cover cropping had a lower success rate (27% average reduction), while the results of application timing were either quantitatively unavailable or inconclusive.

Although water quality is the primary focus of this paper, BMPs were analyzed for their effectiveness in mitigating/preventing water and air contamination, and human and wildlife exposure. **Table 1-1,** summarizes the primary environmental components and modes of impact affected by each BMP analyzed in this report.

Financially, conservation tillage offers growers a potential average savings of $521 per acre. Considering the effectiveness of this method in reducing runoff, it appears to be a viable solution to runoff issues from both environmental and economic perspectives. However, this method has also been associated with increased herbicide use, as well as increased groundwater leaching. Thus, use of conservation tillage must be undertaken with great care to prevent tradeoffs between a surface water quality problem and a groundwater quality problem.

Another financially viable BMP is a preventative BMP: implementation of sensor spray technology. The studies surveyed indicated that pesticide use was reduced by an average of 38% with sensor spray technology compared to use of standard sprayers. The reduction in pesticide use will result in reduced inputs to surface waters and a significant cost savings for the grower. In fact, researchers and statisticians at California State University at Chico determined that the savings resulting from reduced chemical costs will cover the cost of purchasing or retrofitting an existing sprayer with sensor spray technology within a few years. In that study, thenumber of years to the economic break-even point depended on acreage, but sensor spray technology continued to save the grower ≥$32 savings per year thereafter.

Implementation of other BMPs to reduce runoff resulted in added costs rather than cost savings. The water treatments Landguard™ and PAM had the lowest costs (average $5 and $41 per acre, respectively), followed by irrigation efficiency, buffers, and cover crops (ranging from $137/acre to $165/acre averages), while a constructed wetland/tailwater pond was the most expensive practice (average $359 per acre). However, it must be noted that high costs of constructed wetlands do not take into account the long time span of benefits associated with the BMP, nor the potential for the BMP to simultaneously serve multiple farming operations, and thus share costs among multiple growers. The changes in cost associated with application timing as a BMP were unavailable or inconclusive.

As a result of the effectiveness of buffers for reducing/preventing off-site transport of pesticides in runoff and the relatively low cost for these BMPs, a greater depth of information is presented here for this category of BMPs. Based on the model created by Zhang et al. (2009), the authors found that a 20 to 30 meter wide buffer had the highest pesticide removal efficiency, potentially removing 92% to 93% of pesticides from the runoff (**Table 1-4**). This prediction was largely based on herbicides, with the more hydrophobic organophosphates and pyrethroids expected to be removed from a combination of runoff and sediment (**Table 1-5**). For pesticide runoff, buffer width explained over half of the variation in removal efficiency, while vegetation type was not a significant factor.

Another objective of this project was to conduct a cost analysis for the implementation of BMPs. For this context, cost is defined as the installation/first year one-time cost plus any maintenance/annual cost. This analysis is limited, and does not take into account costs or cost savings throughout the useful life of the BMP. A summary of the costs/cost savings associated with the implementation of BMPs known to reduce runoff is presented in **Figure 1-2**. **Table 1-2,** details the findings in the reviewed literature regarding changes in environmental impact and cost upon implementing a given BMP. A representative or average percentage reduction in impact or change in cost is listed along with a range comprised of the minimum and maximum values reported. Negative cost values signify a potential cost savings upon implementation of the BMP, whereas positive cost values imply a cost increase. Not Available (N/A) ratings signify BMPs where more research is needed, as quantitative conclusions could not be made based on the reviewed literature. **Table 1-3** separates cost totals into installation or first year costs and maintenance or yearly costs.

Studies on the effectiveness of buffers for removing sediment from runoff indicate that 30% to 100% (average = 71%) of sediment in runoff is removed by buffers (Gassman et al., 2006, Patty et al., 1997, and (Abu-Zreig et al. 2004)). This relatively high sediment removal efficiency indicates that buffers will also efficiently remove hydrophobic pesticides that bind to sediment (i.e. pyrethroids).

The costs of buffers can be highly variable, depending on the materials and construction that are used. Costs for a non-engineered grassed waterway and an annually planted grassed filter strip were used to estimate a range of general buffer costs, shown in **Tables 1-6 and 1-7** (Tourte et al. 2003c, d). Looking at the representative costs, implementation in the first year ranged from $540/acre to $4,805/acre, while yearly costs ranged from $540/acre to $1,612/acre.

Buffer costs may be offset by several other beneficial effects. The protection from flood and storm related events by buffers were estimated to offset these costs by $390/acre to $1,350/acre.

In addition, if the vegetation in the buffer is chosen to increase the potential of biological control it may reduce pesticide costs. If the vegetation can produce a cash crop income, there is a chance of further offsetting costs. If the buffer takes land out of production, however, the opportunity costs presented in **Table 1-6** should also be taken into account. Finally, assistance from the many federal cost share programs should be considered.

For comparative purposes, the buffer was estimated to be the length of a square 50 acre field, with the 20 meter width recommended by the meta-analysis. It would therefore be 1475 feet long, 65 feet wide, or 95,875 square feet (2.2 acres). The installation cost would range from $436/acre to $10,542/acre, resulting in a total cost of $959 to $10,546 for the 2.2 acre buffer. When the cost is distributed across the entire 50 acres that are being served by the BMP the cost of the BMP is only $19/acre to $211/acre (average: $115/acre). After the installation year, annual maintenance costs range from $19/acre to $77/acre (average $48/acre). In terms of changes in cost between a hypothetical farm with and without a buffer, these cost estimates should be viewed as increases in costs compared to a field without a buffer, holding all other production costs constant.

While comparative conclusions are strongly limited by the availability and quality of data reported in the literature, this report can serve a wide range of stakeholders as a framework of BMP efficiency for preventing off-site transport of pesticides and economic evaluation. This report can also be a useful reference to help the producers effectively meet water quality regulatory requirements and to help regulators identify appropriate water quality management plans. By presenting the relative certainty of the conclusions drawn, this report can also be used to identify where information gaps currently exist, and thus assist in directing future resources toward studies for improvement in these knowledge arenas. Finally, the report offers a thorough, but non-exhaustive, sampling of the relevant BMP literature, as well as links to online tools and websites that can provide readers with a more in depth understanding of the various issues surrounding each BMP.

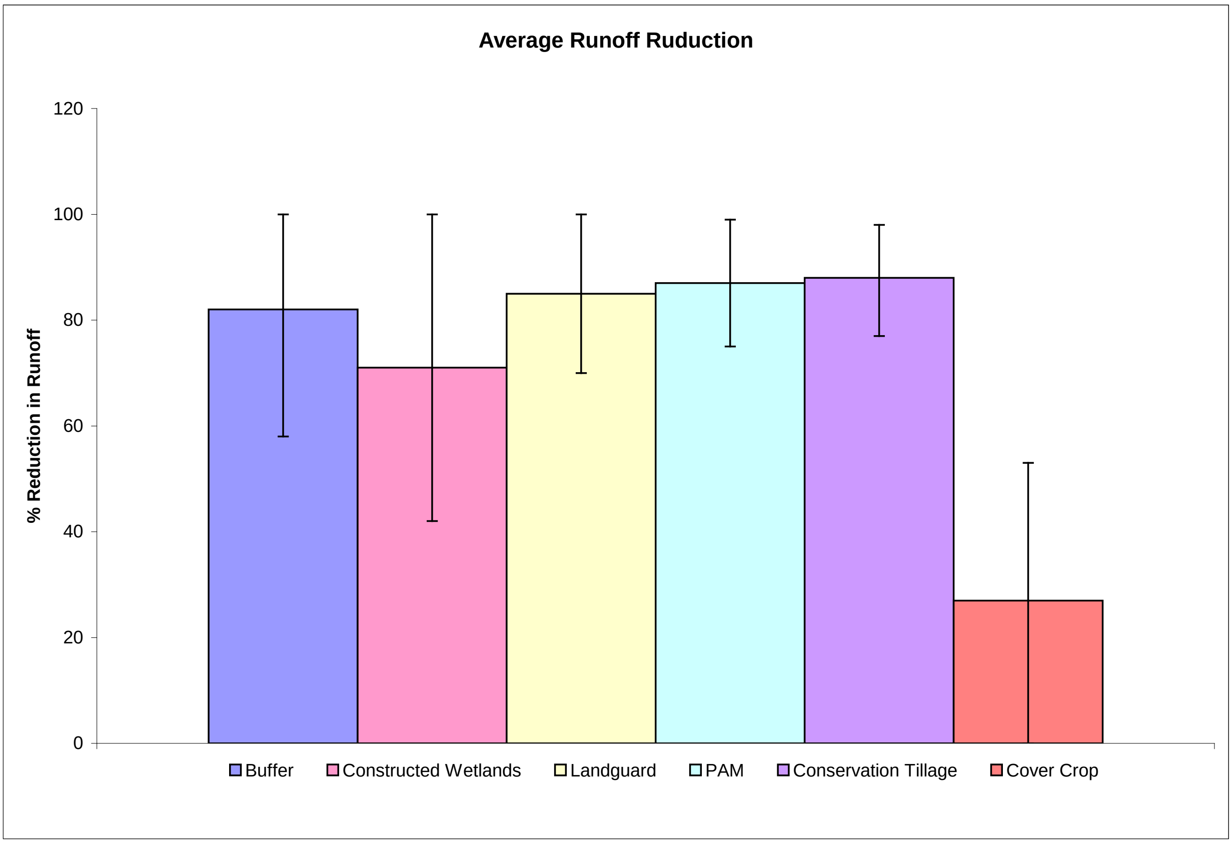


Figure 1-1 Pesticide runoff reduction associated with implementation of various BMPs. Representative/average[1] percentage change in runoff associated with implementation of BMPs known to be effective for reductions in runoff, sediment bound and dissolved pesticides. Error bars represent the data range presented in the reviewed literature. No quantitative data was available for the runoff reduction associated with application timing or irrigation efficiency.

[1] "Average" values are the average of multiple values either from one or more studies, with the minimum and maximum values serving as a range. "Representative" values were defined as such by the author of a study, usually in conjunction with a low and high range estimate.

Table 1-1: BMP implementation: environmental impacts.

	Environmental Component					
	Water Quality		Air Quality		Farm Worker /Wildlife	All
	Mode of Impact					
BMPs	Runoff	Leaching	VOCs	Drift	Exposure	Use Reduction[a]
Buffers	**X**					
Windbreaks				**X**		
Constructed Wetlands/Tailwater Ponds	**X**					
Water Treatments: PAM, Landguard™	**X**					
Conservation Tillage	**X**					
Application: Timing	**X**	**X**			**X**	
Application: Handling					**X**	
Application: Low Drift Sprayers/equipment				**X**		
Application: Sensor Sprayer						**X**
Biological Control						**X**
Pesticide Choice: Low risk and formulation			**X**			**X**
Habitat Removal						**X**
Barriers						**X**
Optimal Irrigation	**X**	**X**				**X**
Optimal Fertilization						**X**
Cover Crop	**X**					**X**
Trap/intercrop						**X**
Synthetic Mulches						**X**
Variety Choice						**X**

[a]Interpreted as a reduction in use of higher risk pesticides - overall pesticide use may not be reduced if alternative lower risk controls are used , such as for the BMP “pesticide choice”

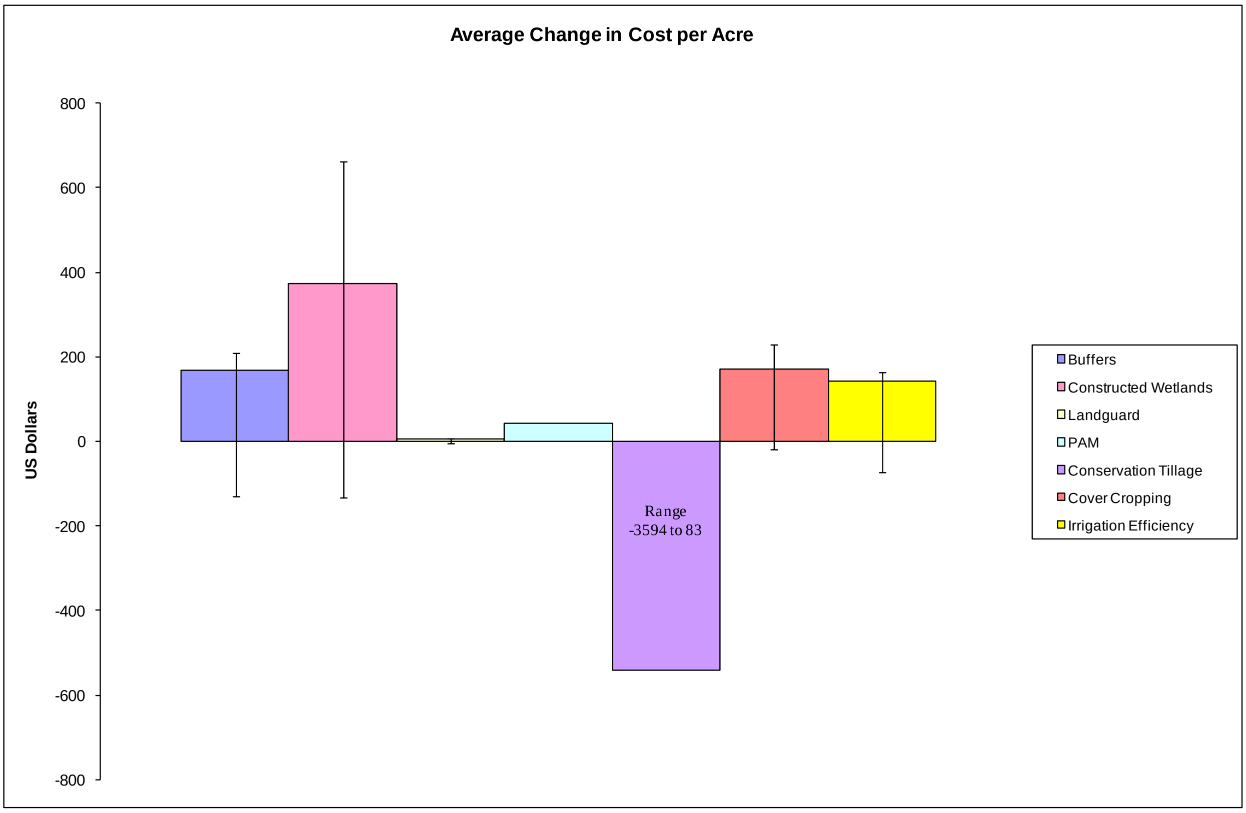


Figure 1-2 Costs associated with BMP implementation.
Representative/average[2] change in per-acre cost associated with implementation of BMPs known to be effective for runoff reduction (and reductions in sediment bound and dissolved pesticides). Negative values indicate a cost savings to the grower. Error bars represent the data range presented in the reviewed literature. No quantitative data was available for the runoff reduction associated with application timing.

[2] "Average" values are the average of multiple values either from one or more studies, with the minimum and maximum values serving as a range. "Representative" values were defined as such by the author of a study, usually in conjunction with a low and high range estimate.

Table 1-2: BMP implementation: costs and changes in environmental impacts. N/A signifies that a range was not available.

BMPs	% Reduction in impact: Representative or average	% Reduction in impact: Range		Total $ per acre change in cost: Representative or average	Total $ per acre change in cost: Range	
Drift						
Windbreak	77	58	96	767	N/A	
Sprayers/Shields	50	N/A		309	129	489
VOCs						
Pesticide Formulation[e]	81	71	92	18	-14	39
Leaching						
Conservation Tillage[b]	N/A			-521	-3462	80
Application Timing[a]	N/A					
Irrigation Efficiency[c]	N/A			137	20	208
Cover crop/ Intercrop/ Trap[cg]	N/A			165	55	184
Sediment or Pesticide Runoff						
Buffer	82	58	100	163	38	288
Wetland/Tailwater w/ Liner	71	42	100	359	278	488
Landguard	85	70	100	5	0.5	10
PAM	87	75	99	41	N/A	
Conservation Tillage[b]	88	77	98	-521	-3462	80
Application Timing[a]	N/A					
Irrigation Efficiency[cf]	N/A			137	20	208
Cover crop/ Intercrop/Trap[cg]	27	0	53	165	55	184
Preventive: Reduced use						
Smart Sprayer	38	25	50	-86	-842	669
Bio Control:Habitat[c]	N/A			767	N/A	
Bio Control:Augmentation[c]	N/A			859	43	1674
Choice of lower risk pesticides[de]	N/A			12	-15	39
Habitat Removal[c]	N/A			57	15	138
Barriers[c]	N/A			423	60	765
Irrigation Efficiency[c]	N/A			137	20	208
Cover crop/ Intercrop/Trap[cg]	N/A			165	55	184
Mulch[c]	N/A			290	275	304
Variety Choice[h]	N/A			-9	N/A	

[a] Assumes a delay in practice without change in cost, however, a substitution of another practice could result in cost decrease or increase
[b] Does not account for potential changes in yield as a result of tillage, which can affect net revenue
[c] Does not account for potential reductions in cost due to reduced pesticide use
[d] Does not account for potential increases in biological control due to use of more selective products, which can reduce the need for pesticides and hence reduce costs
[e] Estimates are for a single pesticide, and so does not encompass the total impact or cost if the grower was to switch all pesticides typically used during a season
[f] Costs represent the change from surface irrigation to sprinklers or microirrigation - assumes implementation of efficient irrigation system generating no unused water through attention to timing and water budget
[g] Estimated costs for cover crop
[h] Estimated cost difference between transgenic and conventional cotton

Table 1-3. Costs: installation or first year costs, maintenance or annual costs, and total costs

BMP	Installation/1st Year			Maintenance/Yearly			Total Costs		
	Rep/ avg	Range		Rep/ avg	Range		Rep/ avg	Range	
Drift									
Windbreak	657	N/A		139	N/A		796	N/A	
Sprayers/ Shields	321	134	508	6	0	13	327	134	521
VOCs									
Pesticide Formulation	19	-15	40	19	-15	40	19	-15	40
Leaching									
Conservation Tillage	-541	-3,594	83	-541	-3,594	83	-541	-3,594	83
Application Timing	Not Available								
Irrigation Efficiency	142	21	216	142	21	216	142	21	216
Cover crop/Intercrop/Trap	171	57	191	171	57	191	171	57	191
Runoff									
Buffer	119	20	219	50	20	80	169	39	299
Wetland/ Tailwater w/ Liner	365	283	497	7	5	9	373	289	507
Landguard	5	1	10	5	1	10	5	1	10
PAM	43	N/A		43	N/A		43	N/A	
Conservation Tillage	-541	-3,594	83	-541	-3,594	83	-541	-3,594	83
Application Timing	Not Available								
Irrigation Efficiency	142	21	216	142	21	216	142	21	216
Cover crop/Intercrop/Trap	171	57	191	171	57	191	171	57	191
Preventive: Reduced use									
Smart Sprayer	-89	-874	694	N/A	N/A		-89	-874	694
Bio Control: Habitat	657	N/A		139	N/A		796	N/A	
Biol Control: Augmentation	892	45	1,738	892	45	1,738	892	45	1,738
Choice of lower risk pesticides	12	-16	40	12	-16	40	12	-16	40
Habitat Removal	59	16	143	59	16	143	59	16	143
Barriers	439	62	794	N/A	N/A		439	62	794
Irrigation Efficiency	142	21	216	142	21	216	142	21	216
Cover crop/Intercrop/Trap	171	57	191	171	57	191	171	57	191
Mulch	301	285	316	301	285	316	301	285	316
Variety Choice	-9	N/A		-9	N/A		-9	N/A	

Table 1-4. Predicted pollutant removal efficiency of buffers.
Predictions based on width, slope, and vegetation of the buffers (Zhang et al. 2010)

		Predicted removal efficiency (%)			
	Buffer width	**5m**	**10m**	**20m**	**30m**
Sediment	(a) Slope = 5%; mixed grass and trees	67	76	78	78
	(b) Slope = 5%; grass/trees only	82	91	93	93
	(c) Slope = 10%; mixed grass and trees	77	86	88	88
	(d) Slope = 10%; grass/trees only	92	100	100	100
	(e) Slope = 15%; mixed grass and trees	58	67	68	68
	(f) Slope = 15%; grass/trees only	73	81	83	83
Nitrogen	(a) Mixed grass and trees/grass only	49	71	91	98
	(b) Trees only	63	85	100	100
Phosphorus	(a) Mixed grass and trees/grass only	51	69	97	100
	(b) Trees only	80	98	100	100
Pesticides	Variety of slopes, vegetation types, and buffer widths/lengths	62	83	92	93

Table 1-5. Reductions in pesticide concentrations in runoff resulting from implementation of buffers.

Pesticide AI	Pesticide Use Type or Class	Buffer Type	Buffer Width or Length (m)	% Reduction	Data Source
Atrazine	Herbicide	Vegetated Filter Strip	6	44	Patty, 1997
Atrazine	Herbicide	Riparian Buffer	7.5	52.0	Schmitt, 1999
Atrazine	Herbicide	Riparian Buffer	15	75.2	Schmitt, 1999
Atrazine	Herbicide	Vegetated Filter Strip	6	97.0	Patty, 1997
Atrazine	Herbicide	Vegetated Filter Strip	12-18	89.2	Patty, 1997
Chlorpyrifos	OP	Vegetated Ditch	Length 400	38.0	Gill et al., 2008
Chlorpyrifos	OP	Vegetated Ditch	Length 30-36	56.0	Moore et al., 2002
Deethylatrazine	Herbicide breakdown product	Vegetated Filter Strip	6	75.0	Patty, 1997
Deethylatrazine	Herbicide breakdown product	Vegetated Filter Strip	12	87.4	Patty, 1997
Deethylatrazine	Herbicide breakdown product	Vegetated Filter Strip	18	99.0	Patty, 1997
Deisopropylatrazine	Herbicide breakdown product	Vegetated Filter Strip	6	70.5	Patty, 1997
Deisopropylatrazine	Herbicide breakdown product	Vegetated Filter Strip	12	83.4	Patty, 1997
Deisopropylatrazine	Herbicide breakdown product	Vegetated Filter Strip	18	98.5	Patty, 1997
Esfenvalerate	Pyrethroid	Vegetated Ditch	Length 600	99.0	Moore et al., 2001
Fluometuron	Herbicide	Vegetated Filter Strip	0.5-1	5.1	Murphy and Shaw, 1997
Isoproturon	Herbicide	Vegetated Filter Strip	6	97.9	Vianello, 2005
Lambda Cyhalothrin	Pyrethroid	Vegetated Ditch	Length 400	25.0	Gill and Bergin, 2008
Lindane	OP	Vegetated Filter Strip	6	82.8	Patty, 1997
Lindane	OP	Vegetated Filter Strip	12	99.5	Patty, 1997

Table 1-6. Buffer cost estimate for installation and maintenance of a grassed waterway. From U.C. Cooperative Extension, Central Coast Conservation Practices for a non-engineered grassed waterway (a1000 linear feet, 10 foot width, 4 foot depth) (Tourte et al. 2003d).

	Costs per unit[a]		
Cost components	**Low cost**	**Representative cost**	**High cost**
Installation Costs (Year 1)			
Clean waterway and smooth banks	$0	$643	$1,542
Plant erosion control mix	$0	$48	$67
Set up sprinklers and irrigate	$0	$63	$114
Installation Costs - Subtotal	$0	$754	$1,724
Annual Operation & Maintenance (Years 2-5):			
Mow vegetation (hand)	$31	$63	$125
Clean waterway	$0	$322	$771
Annual Operating and Maintenance Costs - Subtotal	$31	$384	$896
Interest on Operating Capital @ 7.4%	$1	$7	$8
First Year Costs	$33	$1,145	$2,628
Reduced Costs associated with flood control and storm events	$0	$322	$771
First Year Costs minus flood/storm benefits	**$33**	**$823**	**$1,857**

[a]Costs adjusted for inflation to reflect probable 2008 costs (http://www.westegg.com/inflation/)

Table 1-7. Buffer cost estimate for installation and maintenance of a grassed filter strip. From U.C. Cooperative Extension, Central Coast Conservation Practices for an annually planted grassed filter strip ([a]1,300 linear feet long, 16 feet wide) (Tourte et al. 2003c).

	Costs per unit[a]		
Cost components	Low cost	**Representative cost**	**High cost**
Annual Installation, Operation & Maintenance			
Site prep - Disc	$9	$29	$38
Spot spray - herbicide	$10	$21	$29
plant filter strip	$0	$25	$252
Set up sprinklers and irrigate	$0	$44	$64
Mulch-straw	$0	$124	$204
Mow vegetation (machine)	$9	$20	$28
Hand weed	$0	Not available	$47
Annual Installation, Operation & Maintenance - subtotal	$29	$263	$663
Interest on Operating Capital @ 7.4%	$1	$6	$15
Costs	$30	$268	$678
Reduced Costs associated with flood control and storm events	$0	$193	$257
First Year Costs minus flood/storm benefits	**$30**	**$75**	**$420**

[a] Costs adjusted for inflation to reflect probable 2008 costs (http://www.westegg.com/inflation/)

2 Abbreviations and Definitions

2.1 List of Abbreviations

AI or ai	Active ingredient
BMP	Best management practice
CDPR or DPR	California Department of Pesticide Regulation http://www.cdpr.ca.gov/
CDFG or DFG	California Department of Fish and Game http://www.dfg.ca.gov/
CVRWQCB	Central Valley Regional Water Quality Control Board http://www.swrcb.ca.gov/rwqcb5/
CURES	Coalition for Urban/Rural Environmental Stewardship
EC_{50}	Effective concentration - half maximal
EXTOXNET	Extension Toxicology Network http://extoxnet.orst.edu/
ILRP	Irrigated Lands Regulatory Program http://www.swrcb.ca.gov/water_issues/programs/agriculture/
K_{OC}	Organic carbon absorption coefficient
K_{OW}	Octanol-water partition coefficient
LC_{50}	Lethal concentration – half maximal
N	Nitrogen (nutrient in many fertilizers)
P	Phosphorus (nutrient in many fertilizers)
PUR	Pesticide Use Report (produced by DPR) http://www.cdpr.ca.gov/docs/pur/purmain.htm
SWRCB	California State Water Resources Control Board http://www.swrcb.ca.gov/
TMDL	Total maximum daily load
TU	Toxic units
UCCE	University of California Cooperative Extension
UCD	University of California, Davis http://www.ucdavis.edu/index.html
US EPA or EPA	United States Environmental Protection Agency http://www.epa.gov/
WLA	Waste load allocation

2.2 Definitions

The BMPs presented in this report can be classified as either largely preventive or largely mitigative, with some practices having aspects of both.

Preventive BMPs: Practices that reduce or eliminate the amount of pesticides needed to control pests, and thus lessen pesticide pollutant input into the ecosystem. They include a wide range of practices, such as biological control, pesticide choice, removal of pest habitat, the use of trap crops, intercropping, cover crops, attention to fertilization and irrigation efficiency, the use of resistant varieties, mulches, and the prevention of crop access by a pest through use of barriers. Multiple preventive BMPs are often implemented simultaneously, as they complement each other and thus increase overall pest control efficacy. They are also often associated with mitigative BMPs.

Mitigative BMPs: Practices designed to decrease the environmental impact of a pesticide already applied. They include practices such as the use of buffers, windbreaks, constructed wetlands, conservation tillage, pesticide application methods, tailwater ponds, and water treatments.

Efficacy: For the purposes of this report, the efficacy of a BMP was defined as its ability to control pests. This term is used primarily in reference to the preventive BMPs, as BMPs with good efficacy (good pest control) decrease the need for standard pesticide applications.

Effectiveness or Efficiency: For the purposes of this report, the effectiveness or efficiency of a BMP was defined as its ability to reduce impact to a component(s) of the environment, such as water quality or exposure of aquatic wildlife to a pesticide. Reductions in the percentage of pesticide runoff (dissolved in water or adsorbed to sediment), leaching, drift, VOCs, and exposure were used as proxies for reductions in environmental impact to each component.

K_{ow}: The octanol-water partition coefficient is a measure of hydrophobicity (water repulsion). Pesticides with low K_{ow} values are described as “hydrophilic”. Relative to those with high K_{ow} values, they dissolve more readily in water, have a higher water solubility value, exhibit less tendency to adsorb to soil or sediment, and a lower bioconcentration factor for aquatic life.

K_{OC}: The organic carbon adsorption coefficient or organic carbon-water partition coefficient is important for estimating a chemical compound’s mobility in soil and between soil and water. A high K_{OC} value indicates that the chemical has a strong tendency to adsorb to soil/sediment. In most cases, the more hydrophobic (higher K_{OW}) a compound is the higher its K_{OC} value.

Effective concentration, half-maximal (EC_{50}): The concentration of a toxicant at which 50% of the exposed population exhibits a response.

Lethal concentration, half-maximal (LC_{50}): The concentration of a toxicant required to kill half of the exposed population.

Opportunity Costs: The value of the best alternative choice available to someone who has chosen one of several mutually exclusive options. In addition to any material, implementation, and maintenance costs associated with a BMP, there are often opportunity costs in the form of the value of what is foregone in order to employ the BMP. For example, in implementing BMPs such as buffers and windbreaks, income is foregone if it requires the use of otherwise productive land that could have been planted with the crop. This opportunity cost is very commodity and year specific, however, due to volatility in environmental conditions affecting productivity, and thus costs and yield, as well as volatility in the market affecting the price the grower receives for the commodity. For example, if a grower chooses to construct a vegetative buffer on the edge of a field instead of planting additional rows of alfalfa, the grower must consider not only the cost of the buffer, but also any lost revenue from the eliminated alfalfa rows. This lost income will depend largely on the productivity of the land now being used by the buffer, as well as the market price for alfalfa in a given year.

Total Maximum Daily Load (TMDL): A calculation of the maximum amount of a pollutant that a waterbody can receive and still safely meet water quality standards.

3 Introduction

3.1 Purpose

The objective of this report is to evaluate best management practices (BMPs) associated with the prevention or mitigation of water quality impacts generated by agricultural pesticide use in California. The report examines the costs, key implementation issues, and effectiveness of eight preventive BMPs (biological control, pesticide choice, removal of pest habitat and resources, barriers, optimal fertilization/irrigation regimes, trap plants/intercroppint/cover crops, synthetic mulches, and variety choice) and six mitigative BMPs (buffers, windbreaks, constructed wetlands/tailwater ponds, water treatments, conservation tillage, and pesticide application procedures). For the preventive BMPs in particular, the effectiveness of the BMP is highly crop specific, so seven representative commodities (alfalfa, almond, cotton, grapes, lettuce, tomato and walnut) were included as a further framework for the analysis. A secondary objective of the study is to highlight information gaps, in order to better direct resources toward further research.

3.2 Background

California led the United States in agricultural cash farm receipts in 2006, totaling $31.4 billion, and contributing 13.1% to the national total. With around 400 different commodities produced, it is one of the most agriculturally diverse states. Approximately 60% of the state's total production revenue comes from the Central Valley, an area spanning 18 counties, which is recognized nationally and internationally as one of the world's most agriculturally productive regions (CDFA 2007). This high productivity has come at a cost, however, with increasing scientific evidence linking agricultural pest management practices to unintended degradation of surface water quality and detrimental effects on aquatic and beneficial organisms. Pesticides are transported off-site from agricultural lands in runoff from irrigation and storm events (**Figure 3-1**) as well as by spray drift of aerial applications and by volatilized pesticides (**Figure 3-2**).

Figure 3-1 Agricultural Runoff
(Photo: USDA Soil Conservation Service)

Figure 3-2 Pesticide vapor drift
(Photo: Ohio State University)

The purpose of this paper is to synthesize available data and report on agricultural best management practices (BMPs) that prevent or mitigate surface water quality impacts from agricultural pesticide use. Representative pesticides were selected for the major classes of pesticides that pose a threat to California's surface waters (**Table 3-1**). These pesticides include one herbicide (diuron), three water-soluble organophosphorus (OP) insecticides (chlorpyrifos, diazinon, and malathion), and one hydrophobic pyrethroid insecticide (bifenthrin).

Table 3-1. The representative commodities and Best Management Practices (BMPs) considered in this report.

	Best Management Practices (BMPs)	
Representative commodities	**Mitigative**	**Preventive**
Alfalfa	Buffers	Biological control
Almonds	Windbreaks	Pesticide choice
Cotton	Constructed wetlands and tailwater ponds	Removal of pest habitat and resources
Grapes	Water treatments	Barriers
Lettuce	Conservation tillage	Optimal fertilization and irrigation
Tomatoes	Pesticide application considerations	Trap plants, intercropping, cover crops
Walnuts		Synthetic mulches
		Crop variety choice

These five pesticides were selected because they were determined to be representative of pesticides posing risks to surface water quality in California and because they are included in the Central Valley Pesticide Basin Plan Amendment Project. The BMPs examined in this report are also assessed on their suitability for California's particular conditions (weather patterns, soil types, etc.), specifically in the Central Valley. The three watersheds included in this study are are the Sacramento River, the San Joaquin River, and the Bay Delta (**Figure 3-3**). Much of the BMP data available from California-based studies was obtained from these three basins.

3.2.1 Project Location and Agricultural Context

The studies reviewed in this report were conducted all over the world under agricultural conditions sometimes very different from those in California. The agricultural context of the Central Valley is reviewed below in order to highlight potential differences in BMP effectiveness dependent on local conditions.

California's Central Valley, the state's largest agricultural production area and the region overseen by the Central Valley Water Board, lies between the Coast Range to the west and the Sierra Nevada Mountains to the east. The valley is flat in topography and has an average elevation of 10 feet (3 meters) above sea level.

Figure 3-3 shows California's Central Valley and its major watersheds. The Sacramento River, flowing from the north, and the San Joaquin River, flowing from the southeast, are both fed primarily by runoff from Sierra Nevada snowmelt and join to form the San Joaquin - Sacramento River Delta (or the Bay Delta).

The weather in the Central Valley is Mediterranean: hot and dry during summer, cool and damp in winter. Summer temperatures range from the mid 90s (~35°C) to temperatures as high as 115°F (46°C). Rainfall typically occurs from November to March.

Due to the dry weather and a relatively deep water table in many areas, water is scarce in the Valley. Government irrigation projects have built numerous dams and canals in order to redistribute water, allowing many previously unusable areas to be used for agriculture.

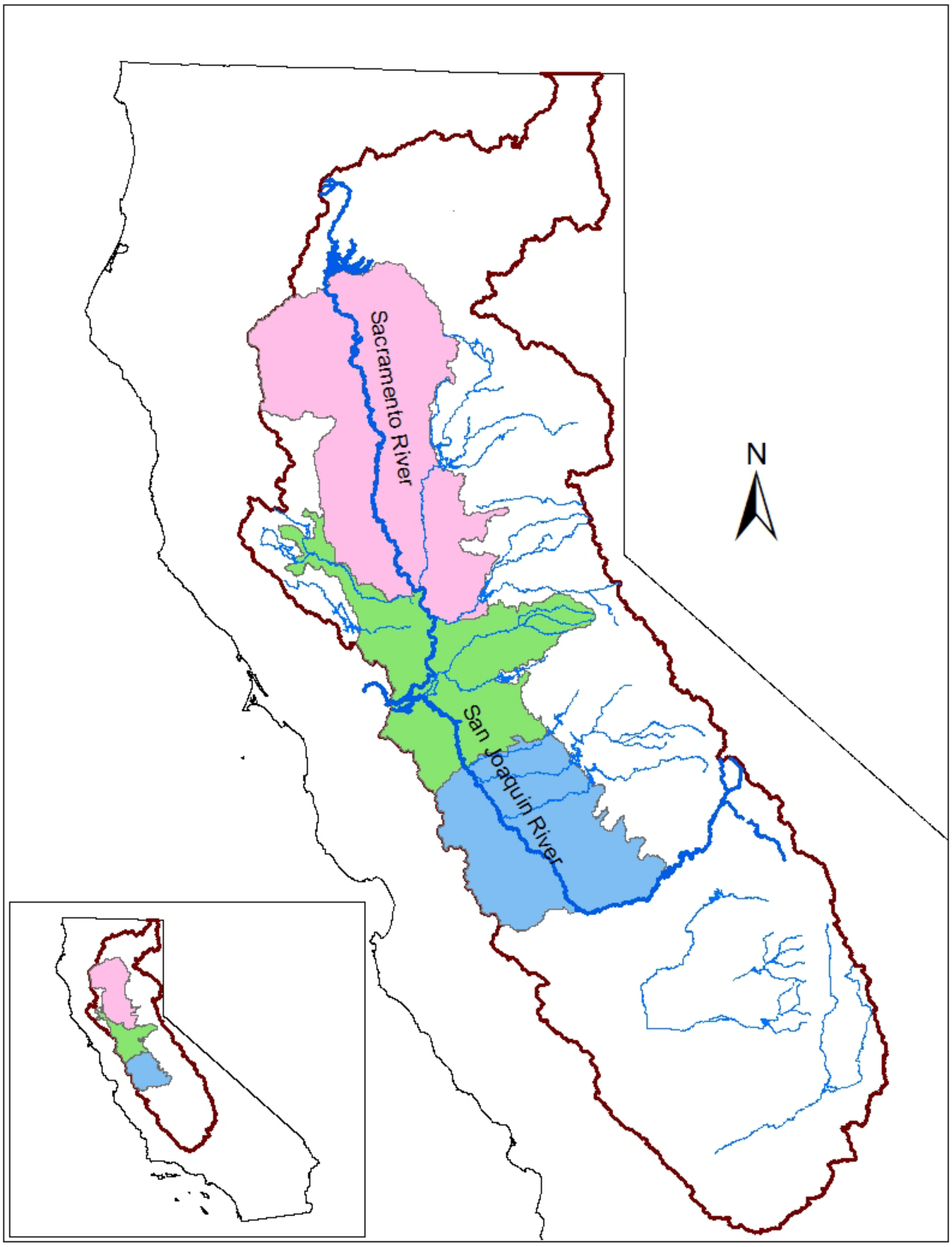


Figure 3-3 A map of the three major watersheds in California's Central Valley region.

To illustrate the importance of regional differences in agricultural conditions which may influence the effectiveness of BMPs, **Table 3-2** presents fundamental differences in rainfall, irrigation, and types of crops between California and the Midwest, another important agricultural area in the US. Differences in irrigation practices and rainfall events, pesticide application practices (especially timing), cropping patterns and types, and soil types create different conditions under which pesticides may be transported into surface water. These differences are significant in determining the effectiveness of a given management practice for reducing off-site transport of pesticides on a particular farm. For example, in California an early dormant season pesticide application on tree crops coincides with the rainy season, which may lead to extensive off-site transport of pesticides in storm-water runoff to surface waters.

Table 3-2. A comparison of the agricultural conditions in California and the Midwest.

Californian Agricultural Context	**Midwestern Agricultural Context**
More than 350 different crops (mainly fruits, nuts, grapes, and dairy)	A few major crops (mainly corn and soybeans)
Primarily irrigation	Primarily rain-fed
Short rainy season (November-February)	Longer rainy season

Therefore, BMP studies conducted in agricultural regions outside of California should be interpreted in the appropriate context with respect to ranfall, irrigation practices, and other region specific factors before applying the results directly to California's agricultural systems.

Equally important to the implementation of appropriate BMPs are the different management styles among California growers. Even if a BMP is deemed suitable for California agriculture, growers may or may not adopt it for economic, business, or personal reasons. Brodt et al. (2004) surveyed California growers on their farming practices over two seasons. From their survey results the authors classified growers into categories based on their management styles and summarized the practices they were most likely to employ: "*Environmental stewards* were more likely to practice biological pest control and encourage wildlife and less likely to use the most toxic chemicals. *Production maximizers* had a greater tendency to use prophylactic and broad-spectrum chemicals, while *networking entrepreneurs* preferred more innovative biological pest controls but tended to avoid time-consuming cultural practices." In order to represent this variability in management practices, we present pesticide use trends for five representative pesticides (diuron, diazinon, chlorpyrifos, malathion, and bifenthrin).

3.3 General Methodology

A thorough, yet non-exhaustive literature review was conducted on the BMPs addressing impacts on water quality and aquatic species. In this report the relative values of various management practices are discussed in terms of *effectiveness*, the ability of the BMP to reduce off-site transport of pesticides, and *efficacy*, the ability of the management practice to eliminate pests.

Based on results reported in the literature, the average or representative change in cost to the grower and change in percentage of environmental impact reduction that would occur upon implementation of the BMP was calculated for each associated environmental component. Negative values indicate a benefit: a given BMP resulted in a reduction of cost or environmental impact. When available, the range of values associated with the studies was included, representing the minimum and maximum changes in environmental impacts and costs.

3.4 Data Limitations and Uncertainty

While extraordinary efforts were made to identify seminal papers and meta-analyses appropriate for California conditions for each BMP, the conclusions of this report must be regarded as being based on a non-exhaustive literature review.

For certain BMPs, there was a wide variation in results from the literature as well as many data gaps.

- For BMPs with large variation in the results from the literature, the average result is supplied along with the minimum and maximum results, thus disclosing the range of variation.
- BMPs with significant data gaps or solely qualitative data are identified as needing further research. Qualitative information concerning the BMP is presented, however quantitative conclusions on efficiency and/or cost were not attempted.
- Due to data limitations, cost data reflects the installation and maintenance costs of the first year of implementation, and does not take into consideration the life span of the benefits of the BMP. With regard to this analysis, it is important to note that some BMPs have very high installation costs, but relatively low long-term mainenace costs, while other BMPs are fairly inexpensive to install, and may have low to high long-term maintenance costs.

3.5 Water Quality

The BMP analysis in this report could help growers and water quality regulatory agencies choose appropriate management plans in areas where pesticide concentrations in surface water exceed regulatory standards. The water quality monitoring results indicate that several waterbodies in California have concentrations of pesticides that are potentially detrimental to aquatic organisms as well as consumers of drinking water (EPA 2006b). Both of the major watersheds in the Central Valley, Sacramento River and San Joaquin River, are listed on the EPA's Clean Water Act 303(d) list of impaired waterways. To address this issue, the California Department of Pesticide Regulation and the California State Water Reources Control Board (with the Regional Water Quality Control Boards) have established regulatory programs aimed at reducing pesticide contamination of surface waters. Total maximum daily loads (TMDLs) have been established for various pesticides (and other water quality parameters/constituents) in California's waterbodies, including TMDLs for diazinon and chlorpyrifos in the

San Joaquin River Watershed and for the Sacramento River and Feather River Watersheds (**Table 3-3**). The TMDLs established in the Sacramento and San Joaquin River Watersheds were established to address toxicity to aquatic organisms. TMDLs include numerical limits for pesticide concentrations in specific water bodies as well as plans to restore the waterbody's beneficial uses and/or repair impairments.

The Central Valley Regional Water Quality Control Board (CVRWQCB) also administers the Irrigated Lands Regulatory Program (ILRP) which requires owners of irrigated lands to meet the following requirements:

- Implement management practices to protect water quality
- Comply with water quality standards
- Conduct monitoring or join a Coalition Group that is conducting monitoring
- Prevent pollution of surface water
- Avoid nuisance conditions, such as odor
- Pay applicable fees

(reference: CVRWQCB Fact Sheet at http://www.swrcb.ca.gov/centralvalley/water_issues/irrigated_lands/general_prog_info/irrlands_disch_fact_sht.pdf).

Table 3-3. Pesticide TMDLs in the Sacramento and San Joaquin River Watersheds

Pollutant	**Watershed(s)**	**TMDL**
Diazinon	Sacramento and Feather Rivers	0.16 μg/l; 1-hour average (acute) 0.10 μg/l; 4-day average (chronic) not to be exceeded more than once in a three year period
Chlorpyrifos	Sacramento and Feather Rivers	0.025 μg/l; 1-hour average (acute) 0.015 μg/l; 4-day average (chronic) not to be exceeded more than once in a three year period
Diazinon	San Joaquin River	1-hour average 0.16 μg/l; 4-day average 0.10 μg/l
Chlorpyrifos	San Joaquin River	0.025 μg/l as a 1-hour average and 0.015 μg/l as a 4-day average

Groups of farmers have formed Coalitions throughout the Central Valley (and California as a whole) to improve and protect water quality in local watersheds while maintaining the economic viability of agriculture. These Coalitions conduct extensive water quality monitoring programs, education and outreach programs, BMP implementation assistance programs, and prepare and administer Management Plans (approved by the Regional Water Board) to address cases where water quality standards set forth in the Water Quality Control Plan for the Sacramento and San Joaquin River Basins (Basin Plan) are exceeded.

3.6 Pesticide Impact on Aquatic and Beneficial Organisms

Studies have shown negative effects of pest management practices on aquatic wildlife and beneficial insects, including those important for pollination and pest control. Pesticides have been shown to cause mortality and low reproductive success of various organisms, which reduces biodiversity and threatens endangered species. For example, in the Central Valley, many of the 5 aquatic invertebrate, 4 amphibian, and 4 fish species listed as threatened or endangered as of 1997 have been affected by pesticide exposure (Umbach 1997, USFWS 2008). In addition, pesticide use has been linked to amphibian declines in areas downwind of the Central Valley (Sparling et al. 2000, Fellers et al. 2004, WTC 2006).

Pesticide use has also been shown to harm beneficial insects and pollinators, including a potential role in honey bee colony collapse disorder. Thus, pesticides have been shown to affect many species that play important economic roles in agriculture through natural pest management and pollination services (UCIPM 2005, EPA 2008).

In summary, agricultural pesticide use has significant negative impacts on a wide range of wildlife, contributing to loss of community natural resources and potential ecosystem functions and services.

3.7 Pesticide Transport and Toxicity

There are many different possible destinations of pesticides before, during, and after an application, including systemic uptake by plants; ingestion by insects, microorganisms, and/or worms; evaporation/volatilization into the atmosphere; adsorption to soil particles; offsite movement via drift or precipitation/irrigation runoff; or leaching into the groundwater (**Figure 3-4**).

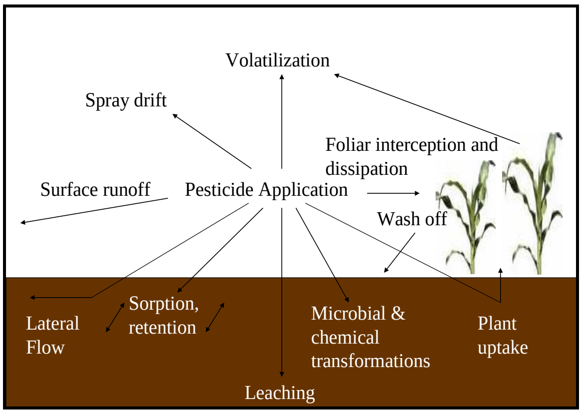


Figure 3-4 Fate and transport of pesticides
http://extension.oregonstate.edu/catalog/html/em/em8561-e/

What ultimately happens to the pesticide depends on a combination of its chemical properties; the environmental, topographic, and meteorological characteristics of the application site; and the management practices of the grower. This section describes some of the properties governing a pesticide's ability to move in water and soil. These properties are important for determining if a pesticide requires BMP implementation, and, if so, which BMPs will be best suited to reduce off-site movement of the pesticide.

3.7.1 Physical properties

The likelihood that a pesticide will volatilize or go into solution in water or adsorb to soil will determine its tendency to move off-site from agricultural lands into surface waters. Two coefficients, the organic carbon adsorption coefficient (K_{OC}) and the octanol-water partition coefficient (K_{OW}), are commonly used to determine the tendency of a pesticide to move in soil and water. Henry's constant, K_h, is used to determine the tendency of a pesticide to volatilize and, therefore, its tendency to be transported in the air. More detailed descriptions of K_{OC}, K_{OW}, and K_h are presented below.

K_{OC}: The organic carbon adsorption coefficient, or organic carbon-water partition coefficient, is important for estimating a chemical compound's mobility in soil and between soil and water. A low K_{OC} value indicates a weak tendency to adsorb to soil/sediment, and, conversely, a high K_{OC} value indicates a strong tendency to adsorb to soil/sediment. The K_{OC} is essentially the ratio of the amount of chemical adsorbed per unit weight of organic carbon in the soil/sediment to the concentration of the chemical in solution at equilibrium. Generally, the higher the K_{OW} value (more hydrophobic) of a compound is the higher its K_{OC} value. However, in some cases, molecular polarity can affect this relationship.

K_{ow}: The octanol-water partition coefficient is a measure of hydrophobicity (water repulsion). It can be interpreted as the tendency of a pesticide to partition between an organic phase (i.e. soil or an organism) and an aqueous phase (i.e. water). Pesticides with low K_{ow} are hydrophilic (meaning that they readily dissolve in water), with higher water solubility, smaller tendency of adsorbing to soil or sediment, and a lower bioconcentration factor for aquatic life relative to those with high K_{ow}. Thus, hydrophilic pesticides can dissolve in the water column, and potentially move offsite via surface runoff or groundwater leaching. Conversely, pesticides with higher K_{ow} are relatively hydrophobic, which imparts a greater tendency to adsorb to soil or sediment, and potentially bioaccumulate in aquatic organisms. Hydrophobic pesticides are more likely to move offsite via runoff, attached to sediment, rather than dissolved in the water column.

K_h: Henry's constant measures volatility, and hence potential movement into the atmosphere. Pesticides with larger K_h values are generally more volatile and their movement tends to be more limited by soil conditions than atmospheric conditions due to less dependence on water evaporation moving the pesticide to the surface (Spencer et al. 1988). Volatilization typically increases as temperature increases and decreases as adsorption to soil or sediment increases.

3.7.2 Toxicological properties

Various measurements of a the toxicity of a pesticide to both target and non-target species are determined to assess the effectiveness of the pesticide for its intended purpose and to assess the danger it poses to non-target species that may be exposed to the pesticide on the agricultural land or off-site when the pesticide is moved in drift or runoff. Common measurements for effectiveness and acute toxicity of chemicals (including pesticides) are the effective concentration (EC), lethal concentration (LC) or lethal dose (LD), no observable (adverse) effect level NO(A)EL, and no observable (adverse) effect concentration NO(A)EC values. These measurements are described further below.

EC_{50}, LC_{50} and LD_{50}: The concentration (EC, LC) or dose (LD) of a pesticide that affects or or kills 50% of the sample population. These values are used as general indicators of a pesticide's effectiveness or acute toxicity to various life forms.

NO(A)EL and NO(A)EC: The highest level or concentration at which the pesticide has no observable adverse effect. These values are often used to assess chronic effects on various life forms.

The Footprint Pesticide Properties Database, developed by the Agriculture and Environment Research Unit of the University of Hertfordshire, UK, offers guidelines for levels of concern (presented in **Table 3-4**) with regard to unintended environmental effects and toxicity to non-target species of pesticides (FOOTPRINT 2009).

Table 3-4. Levels of concern for pesticide toxicity to non-target species. Determined by the Footprint Pesticide Properties Database (FOOTPRINT 2009)

Variable	Low	Moderate	High	Source
K_{oc}/K_{foc} (ml g^{-1})	500 - 4000	75 - 500	< 15 very mobile 15 – 75 mobile	PSD Pesticide Data Requirement Handbook (2005). SSLRC Mobility Classification System. Note 1.
Log K_{ow}	< 2.7 (hydrophilic)	2.7 to 3	> 3 (hydrophobic)	Used by the US EPA.
K_h at 25°C	< 0.1 (non-volatile)	0.1 to 100	> 100 (volatile)	Rule of thumb in wide, general use.
Mammals LD_{50} mg kg^{-1}	> 2000	100 to 2000	< 100	Note 1.
Mammals NOEL mg kg^{-1}	> 2000	100 to 2000	< 100	Note 1.
Birds LD_{50} mg kg^{-1}	> 2000	100 to 2000	< 100	Consistent with US EPA Guidelines. Note 1.
Fish LC_{50} ppm	> 100	0.1 to 100	< 0.1	Note 1.
Fish NOEC ppm	> 10	0.01 to 10	< 0.01	Note 1.
Aquatic Invertebrates EC_{50} ppm	> 100	0.1 to 100	< 0.1	Note 1.
Aquatic Invertebrates NOEC ppm	> 10	0.01 to 10	< 0.01	Note 1.
Sediment Dwellers LC_{50} ppm	>100	0.1 to 100	< 0.1	Note 1.
Aquatic plants EC_{50} (mg l^{-1})	>10	0.01 – 10	<0.01	Note 2.
Algae EC_{50} (mg l^{-1})	>10	0.01 – 10	<0.01	Note 2.
Algae NOEC (mg l^{-1})	>1	0.001 – 1	<1	Note 2.

Notes

1. Thresholds used have been selected to be consistent with industry guidelines, were developed, and are consistent with regulatory thresholds used in both the UK and EU.
2. The EU (Uniform Principles) (Annex VI of Directive 91/414/EEC) guidelines that have been adopted have set toxicity exposure (TER) ratios for algae and aquatic plants at 1/10th of those for fish and daphnids. The same ratio has been applied here.

3.8 Representative Pesticides and Commodities

Pesticides: Given the wide variety of pesticides used by California growers, the BMPs described in this report were evaluated for their abilities to prevent or mitigate impacts to surface water quality for five pesticide active ingredients. These pesticides represent one herbicide (diuron), three water-soluble organophosphorus (OP) insecticides (chlorpyrifos, diazinon, and malathion), and one hydrophobic pyrethroid insecticide (bifenthrin). The five pesticides were selected because they were determined to be representative of high-risk pesticides to surface water quality and they are commonly used in the Central Valley Pesticide Basin Plan Amendment Project Area.

Commodities**:** Representative commodities were also employed in evaluating both BMP *efficacy,* for pest control in the absence of or with reduced use of standard pesticide application processes, and BMP *efficiency,* for preventing or reducing off-site movement of pesticides. The efficacy of preventive BMPs for pest control was often highly crop specific. A small selection of commodities, including lettuce, tomatoes, alfalfa, almonds, walnuts, grapes, and cotton, was chosen to representative of annual field crops, orchards, and non-orchard perennials. **Table 3-5** shows the total pounds applied of each representative pesticide to each representative commodity during 2007. All of the representative commodities were in California's top 20 for cash revenue in 2005-2007 (Agricultural Statistical Review: http://www.cdfa.ca.gov/statistics/files/CDFA_Sec2.pdf) and are major crops in the Central Valley. **Table 3-6** lists the estimated total revenue for each of the representative commodities for 2007. In addition, a range of the net returns over the total costs are given for those commodities for which 2007 University of California, Davis, Agricultural and Resource Economics cost and return studies were available. Net returns over costs are the best estimator of the opportunity cost, but data was not available for all commodities in the same year. Looking at the net returns for 2007, it is apparent that there is a wide range of financial outcomes, ranging from losses (negative values) to profits (positive values), within a given commodity and year. The opportunity cost is a less important consideration for regions of marginally productive land, or years when commodity prices are low.

Table 3-5. Pounds of representative pesticides applied to representative commodities. Central Valley, 2007 (PUR Database/CalPIP).

Chemical Name	Pounds Chemical Applied	Acres Treated	Crop
bifenthrin	8	90	alfalfa
	1,166	16,622	almond
	28	452	cotton
	4,008	6,989	tomatoes
	1,502	15,963	walnut
chlorpyrifos	23,310	47,855	alfalfa
	56,395	32,735	almond
	482	635	cotton
	21,313	11,009	grapes
	108,166	60,647	walnut
diazinon	6,500	2,554	almond
	72	101	grapes
	650	288	lettuce
	6,025	3,899	tomatoes
	4,282	2,111	walnut
diuron	45,921	38,545	alfalfa
	21	582	cotton
	15,433	20,246	grapes
	10,704	9,715	walnut
malathion	12,066	12,747	alfalfa
	3,572	481	grapes
	21,757	4,605	walnut

Table 3-6. BMP costs and net returns (2007).

Representative Commodity	Cash Income ($1000)[e]	Acres Harvested (1000)[e]	Total revenue/ acre (Income/acres harvested)	(Net Returns over costs)/acre
alfalfa	862,943	1,610	536	65 to 95[a]
almonds	2,127,375	615	3,459	
cotton	615,306	451	1,364	
grapes	3,082,014	789	3,906	-129 to 3132[b]
lettuce	2,178,041	290	7,510	
tomatoes	1,241,735	337	3,685	-78 to 871[c]
walnuts	754,000	218	3,459	1,073 to 1,359[d]

[a](Orloff et al. 2007a, Orloff et al. 2007b), [b](Hashim-Buckey et al. 2007, Peacock et al. 2007a, b, Vasquez et al. 2007), [c](Miyao et al. 2007, Stoddard et al. 2007), [d](Grant et al. 2007, Krueger et al. 2007),
[e] (USDA 2007)

4 Use Trends and Chemical Properties of Representative Pesticides

Use Trends: Spatio-temporal use trends were analyzed for the top five high-use commodities of each representative pesticide (Appendix). For some pesticides, negligible use resulted in less than five commodities being analyzed.

Spatial: Pesticide use trends for each of the representative pesticides were analyzed for the Lower Sacramento River, the Lower Delta, and the Lower San Joaquin River watersheds (**Figure 4-1**).

Temporal: Pesticide use trends were analyzed from 1995 to 2006. Trends were evaluated for both wet (November-March) and dry (April-October) seasons.

Data: Pesticide use information was obtained from the Pesticide Use Report (PUR) Database maintained by CDPR. The PUR database offers a wealth of field level data reported by California growers, including information on product choices, use amounts, acres treated and planted, commodity type, date, and location (CDPR 2009c). Data was checked for errors and outliers using an extensive data cleaning methodology developed by CDPR (Wilhoit 2002). All erroneous data were deleted from the analysis, while outliers were replaced by median use rates of active ingredients for the specific product, crop, and year.

Chemical Properties: In addition to use trends, the chemical properties for these five pesticides were described by combining values reported in the Footprint Pesticide Properties Database, developed by the Agriculture and Environment Research Unit of the University of Hertfordshire, UK, and the Extoxnet pesticide information profiles, developed by the University of California, Davis, Oregon State University, Michigan State University, Cornell University, and the University of Idaho (EXTOXNET 1996, FOOTPRINT 2009). A summary of the primary environmental concerns for each representative pesticide is presented in **Table 4-1**.

Table 4-1. Levels of concern for the 5 representative pesticides.
L = low concern, M = moderate concern, H = high concern (EXTOXNET 1996, FOOTPRINT 2009)

Representative Pesticide	Surface Water (log K_{ow})	Sediment (K_{oc})	Ground Water (GUS leaching potential index[a])	Volatilization (Henry's Law Constant at 25°C)	VOCs (Vapor pressure at 25°C)	Human /Mammal Health	Birds	Aquatic species	Arthropods/ other
Diuron	M	M-H	M	L	M	L-M	L-M	M	L-M
Bifenthrin	H	H	L	L	M	M-H	L-M	H	H
Chlorpyrifos	H	H	L	M	H	H	H	H	H
Diazinon	H	M	L	L	H	H	H	M-H	L-H
Malathion	M	L-M	L	L	H	M-H	M	M-H	M-H

[a] This parameter is an indicator and is used here only to provide a general indication of hazard. It is based solely on the physical-chemical properties of the compound and does not account of the local environmental conditions, the field application rate, application timing or formulation. Therefore, it should not be taken as a substitute for a full risk assessment.

Note: Thresholds used for determining the level of concern (L, M, or H) have been selected to be consistent with industry guidelines, and are consistent with regulatory thresholds used in both the UK and EU.

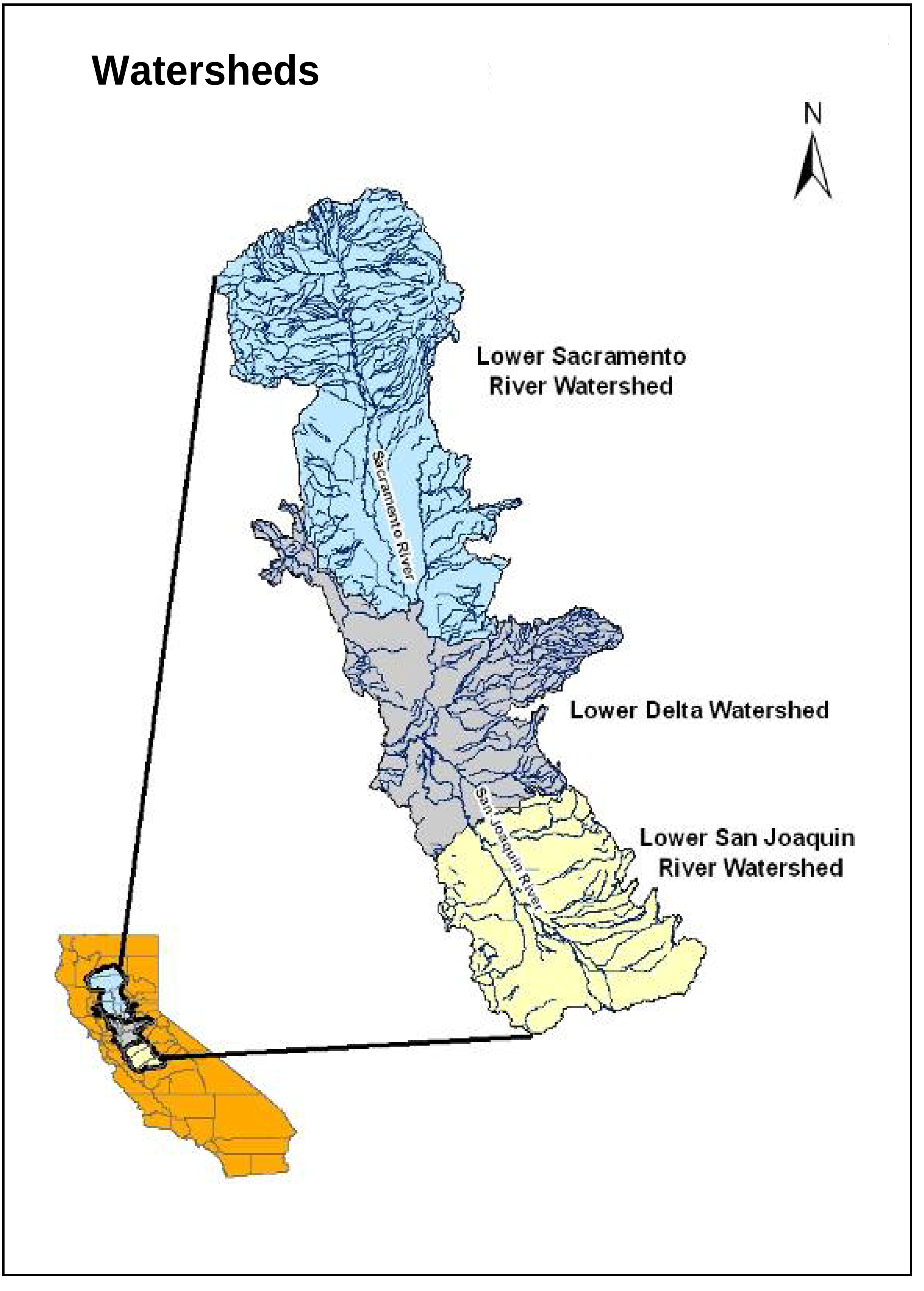


Figure 4-1 **Central Valley Pesticide Basin Plan Amendment Project Area Watersheds**

4.1 Diuron

Diuron is a systemic, substituted phenylurea herbicide which works by inhibiting photosynthesis in a wide variety of annual and perennial broadleaf and grassy weeds. It is the active ingredient in many common pre-emergent herbicides and defoliants, such as Direx 4L, Ginstar EC Cotton Defoliant, Drexel Diuron 4L, Karmex XP and DF, and Krovar I DF. Formulations include wettable powders, suspensions, and emulsifiable concentrates.

4.1.1 Use Trends

Figure 4-2 shows the temporal use trends of diuron in various crops for the three Central Valley watersheds between 1995 and 2006. In general, diuron use was higher during the wet season than in the dry season due to its elevated use on alfalfa in all three watersheds.

In the Lower San Joaquin River watershed, walnuts, wine grapes, other grapes, and oranges were among the top five high-use crops for both the wet and dry seasons. Alfalfa had high use only in the wet season, and cotton had high use only in the dry season.

In general, there was less use on agricultural crops in the lower Sacramento River watershed compared to the other two watersheds, with use on rights-of-way and uncultivated non-agricultural areas ranking in the top five. Walnuts, olives, and uncultivated non-agricultural areas had high use in both wet and dry seasons. Alfalfa and rights-of-way had high use only in the wet season, while cotton and oranges had high use only in the dry season.

Finally, in the Lower Delta watershed, walnuts, asparagus, wine grapes, other grapes, and alfalfa had high use in both the wet and dry season, although dry season use on alfalfa appeared to stop after 2002 (**Figure 4-2**).

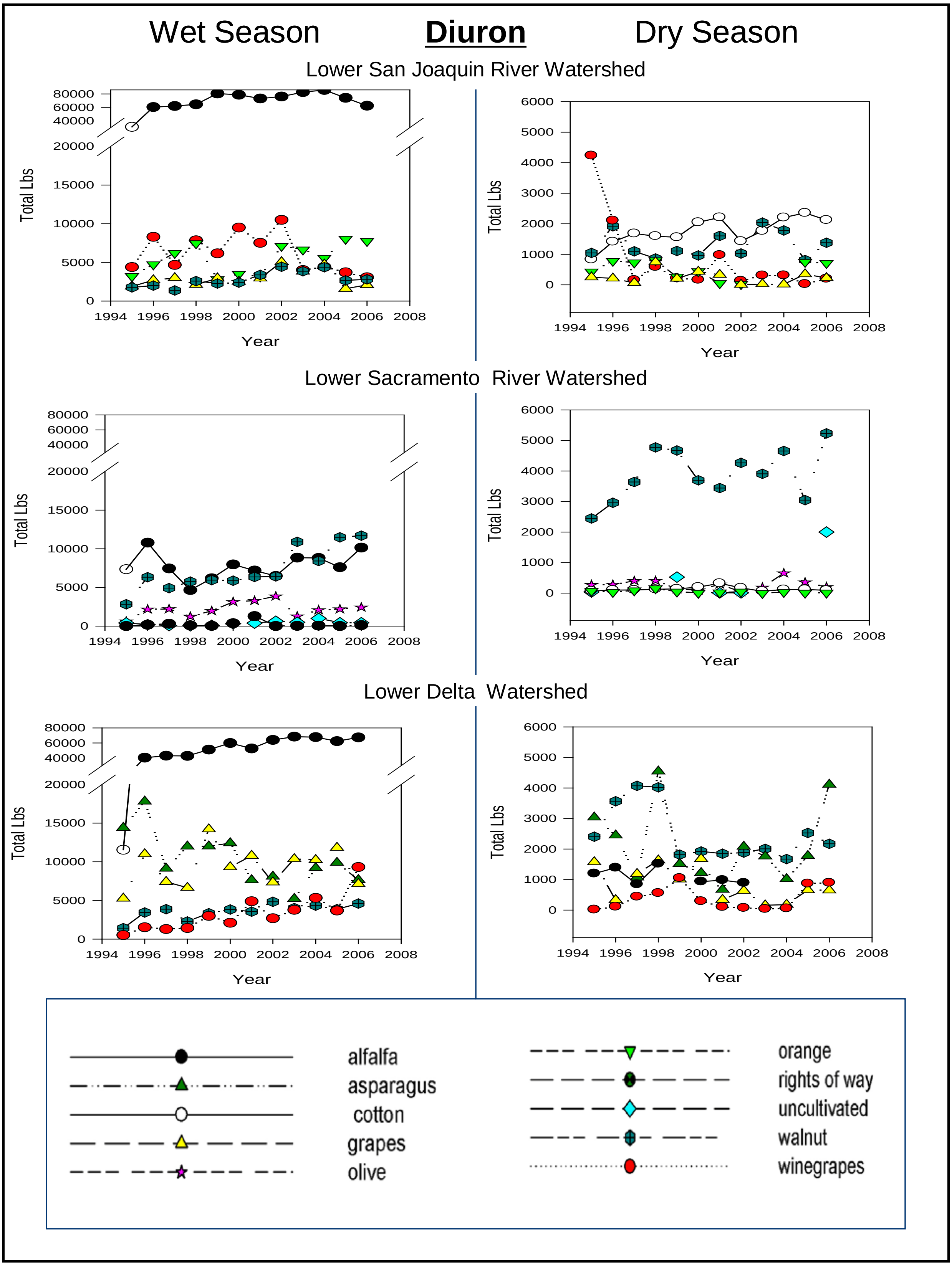


Figure 4-2. Diuron pesticide use trends: 1995 to 2006.
Note: different Y axis scales.

Figure 4-3 shows the spatial change in total diuron use between 1995 and 2006 for the wet and dry seasons in the Central Valley. Diuron use during the wet season increased significantly from 1995 to 2006, especially in Yolo, San Joaquin, Merced and northern Fresno counties. There was much less change in the dry season use than in the wet season use. Dry season diuron use was mainly located in the Lower Delta and the Lower San Joaquin River watersheds. The largest increases over the 12-year period appeared as more high use areas during the wet season in the Lower Delta watershed.

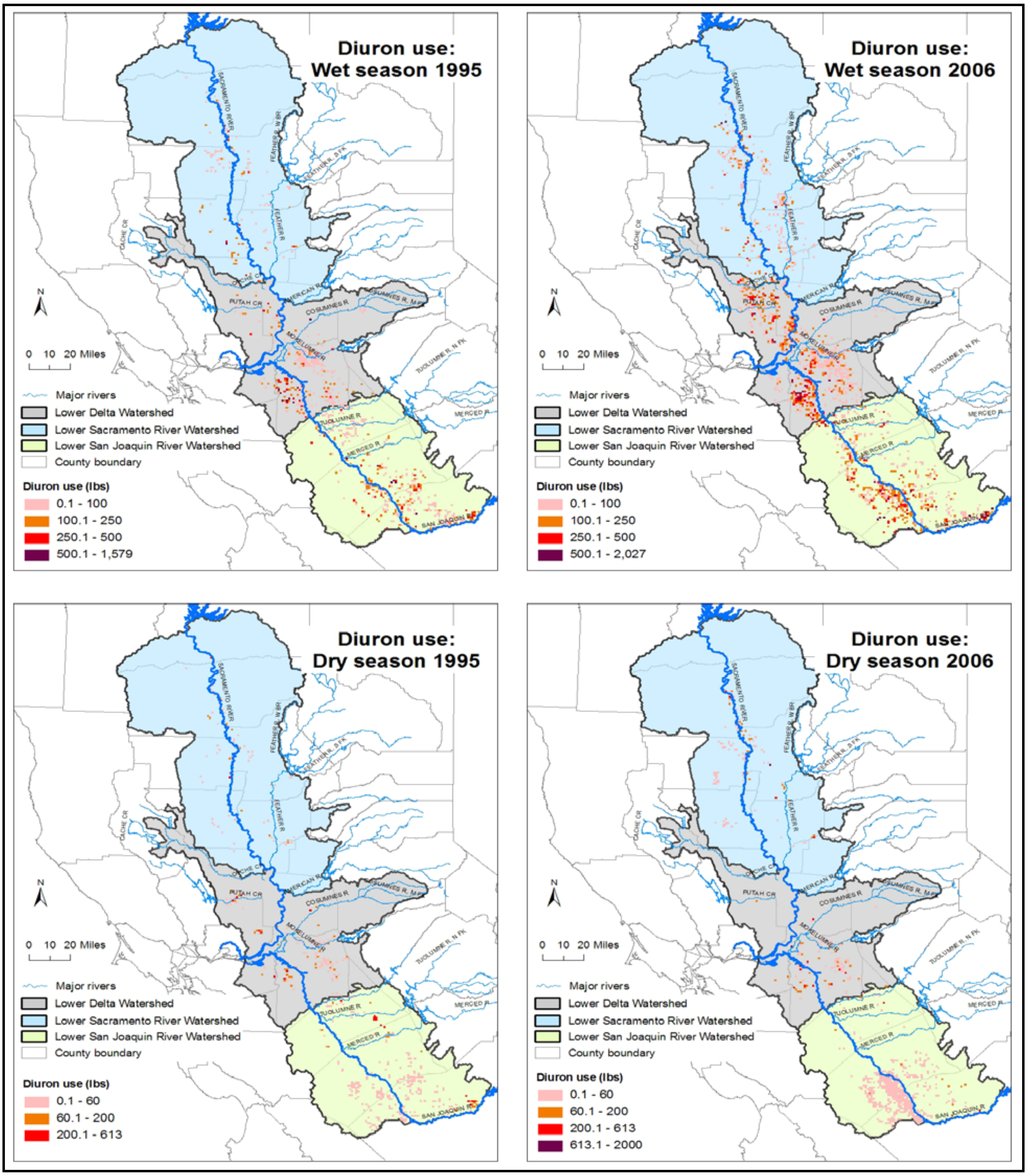


Figure 4-3 Diuron: spatio-temporal use trend maps.

4.1.2 Toxicity and Environmental Exposure

- **Water and sediment quality**

Diuron has a log K_{ow} of 2.87 (pH 7, 20° C), indicating that it is moderately hydrophilic, and could potentially be of concern for runoff to surface water or leaching to groundwater. Diuron has also been shown to adsorb to sediment (Peck et al. 1980) and therefore could potentially be mobilized by transport of contaminated sediment. Diuron has not been identified in the EPA 303(d) list as impairing surface water quality to the point of requiring the establishment of a total maximum daily load (TMDL) standard (EXTOXNET 1996, EPA 2006a, CDPR 2007a, FOOTPRINT 2009). Between 1992 and 2006, the average concentration of diuron observed in surface waters of the Central Valley (CVRWQCB area) was 0.8430 ppb with a range of 0 to 160 ppb observed in surface water samples (CDPR Surface Water Monitoring Program, accessed 12/29/09). The highest concentrations of diuron were found in water samples collected in San Joaquin County, and positive detections were prevelant throughout the Sacramento and San Joaquin River Watersheds.

- **Aquatic species**

Diuron is an herbicide which is toxic to aquatic plants. The 96-hour EC_{50} with 96.8% ai diuron for the sensitive green alga *Selenastrum capricornutum* is 2.4 ppb ai. (http://www.epa.gov/espp/litstatus/effects/redleg-frog/diuron/appendix-l.pdf). Diuron is moderately toxic to fish and aquatic invertebrates, with a 48-hour LC_{50} range from 4.3 to 42 ppm for fish and from 1 to 2.5 ppm for invertebrates (EXTOXNET 1996, FOOTPRINT 2009). Its environmental breakdown product, 3, 4-dichloroaniline, may be toxic to aquatic organisms and sediment dwellers (Giacomazzi and Cochet 2004).

- **Beneficial species**

Diuron has low to moderate toxicity to bees and earthworms, and is harmless to natural predators of pests (EXTOXNET 1996, FOOTPRINT 2009).

4.2 Bifenthrin

Bifenthrin is a pyrethroid insecticide that is toxic through both ingestion and contact as a sodium channel moderator. It is the dominant active ingredient in products such as Fanfare 2EC, Capture 2EC, and Brigade WSB, among others. It controls pests such as Acari (mites), and pests from many orders of insects, such as Lepidoptera (moths), Orthoptera (grasshoppers, crickets), Heteroptera (plant bugs), Thysanoptera (thrips), Coleoptera (beetles and weevils), Homoptera (scale, whiteflies, aphids), and

Hymenoptera (ants). Several formulations are available, including a wettable powder, granule flowable, or emulsifiable concentrate.

4.2.1 Use Trends

Figure 4-4 shows the temporal use trends of bifenthrin in various crops for the three Central Valley watersheds between 1995 and 2006. Use was nearly negligible in the wet season, often less than a total of 10 pounds applied, and mainly for greenhouse or container plants. In general, pyrethroids have much lower application rates than other pesticides, so total pyrethroid use will commonly be lower than use of the other classes of pesticides.

Use of bifenthrin in the Lower San Joaquin River watershed on the top five commodities was very low and sporadic in the wet season, with occasional use on broccoli, cucumber, corn, and outdoor or greenhouse container plants. Dry season use was more continuous, with use on corn increasing since 2000, and use on cotton and alfalfa decreasing over time. This use trend may reflect rotations of these three crops and recent higher prices for corn due to biofuel use. Cantaloupe and melons showed relatively steady use over time.

In the lower Sacramento River watershed, there was very low occasional use of bifenthrin in the wet season on greenhouse cut flowers and greenhouse and outdoor container plants. During the dry season, watermelons, cucumbers and squash maintained relatively steady use over time. In contrast, melons and clover fluctuated more dramatically and nearly in opposition to each other, possibly due to rotations between the two crops.

Finally, the lower Delta watershed exhibited wet season use of bifenthrin on greenhouse cut flowers and transplants, as well as on outdoor and greenhouse container plants. Dry season use was seen on watermelons and other melons, in addition to increasing use on pumpkins and corn grown for either human consumption or forage (**Figure 4-4**).

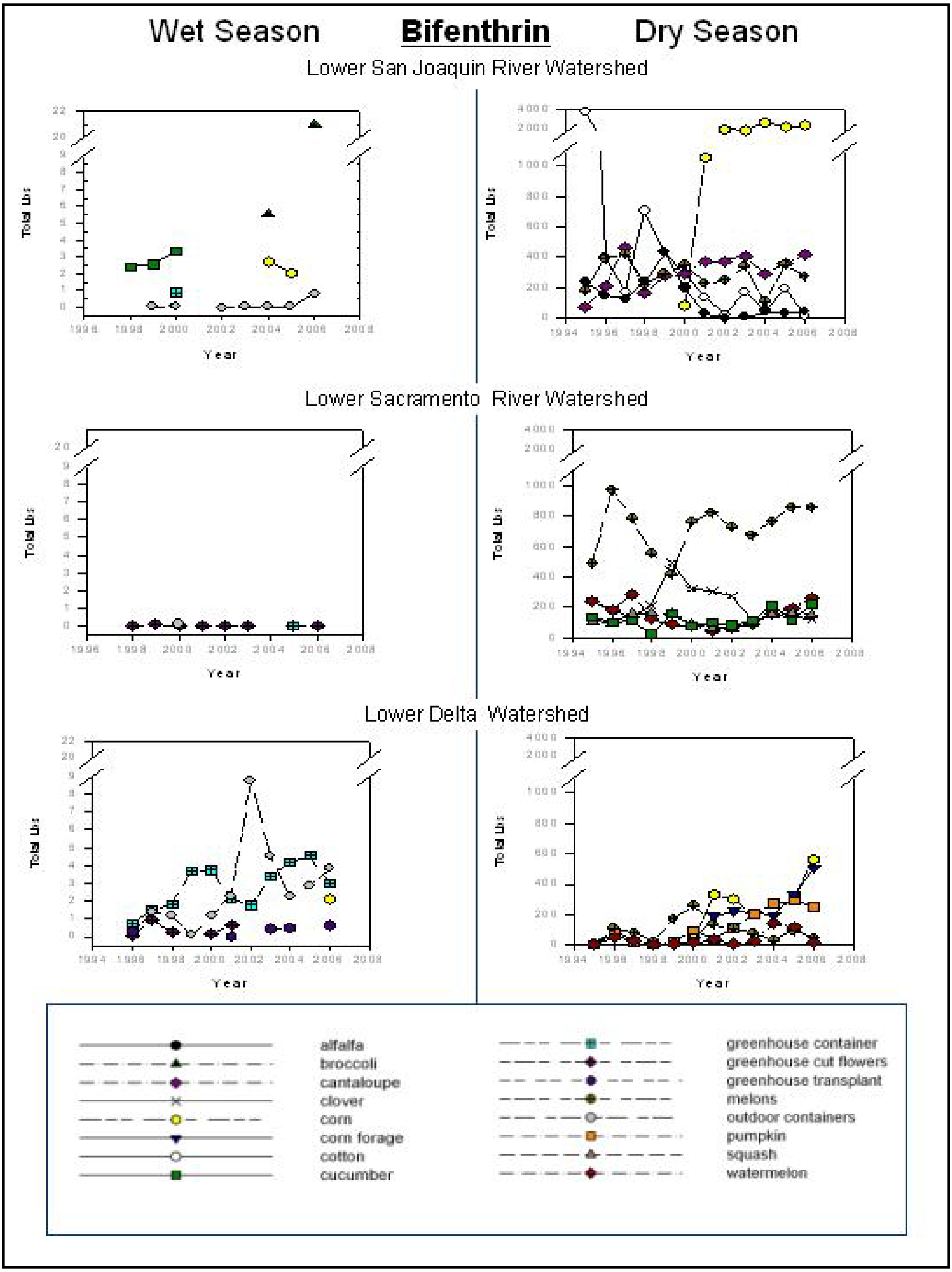


Figure 4-4. Bifenthrin: pesticide use trends 1995 to 2006.
Note: different Y axis scales for wet and dry seasons.

Figure 4-5 shows the spatial change in bifenthrin pesticide use between 1995 and 2006 for the dry season only, since there was negligible use in the wet season. In 1995, bifenthrin was mainly used in the Lower Sacramento River watershed and the Lower San Joaquin River watershed, in Glenn, Sutter, Yuba, Merced and Fresno counties. Significant increases of bifenthrin use occurred in the Lower Delta watershed and northeast portion of the Lower San Joaquin River watershed, Contra Costa, San Joaquin, Stanislaus and Colusa counties. In contrast, significant decreases in bifenthrin use were observed in Merced and northern Fresno counties.

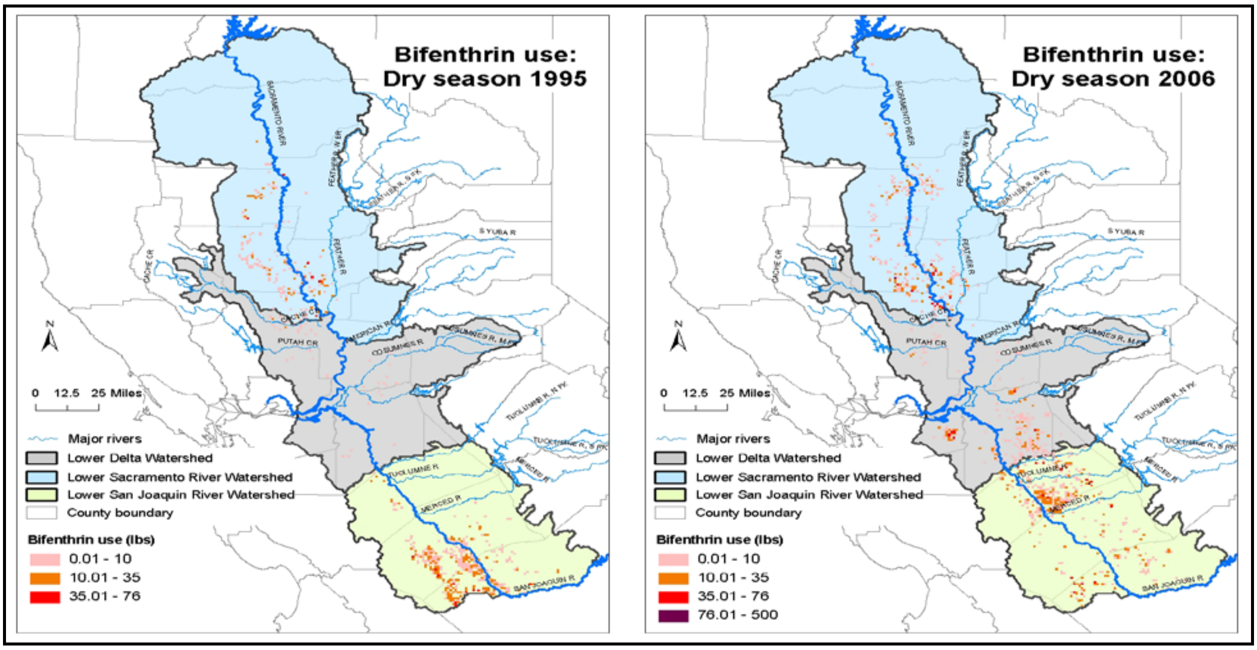


Figure 4-5. Bifenthrin: spatio-temporal use trend maps.
Wet season not evaluated due to near negligible use.

4.2.2 Toxicity and Environmental Exposure

- Water and sediment quality

Bifenthrin has a relatively high log K_{ow} of 7.3 (pH 7, 20^{o} C), indicating that it is hydrophobic and likely to adsorb to soil or sediment (FOOTPRINT 2009). Bifenthrin has not been listed on either the CDPR 6800 groundwater list or the EPA 303(d) list. However, like many synthetic pyrethroids, it can move offsite to water bodies while attached to sediment. As a result, it has been found at toxic levels in the sediment of water bodies in many agricultural areas of California (Siepmann and Holm 2000, Starner and Kelley 2005, Grover et al. 2007). Between 2003 and 2006, the average concentration of bifenthrin observed in the Central Valley surface waters (CVRWQCB area) was 0.0009 ppb with a range of 0.00 to 0.43 ppb observed in water samples (CDPR Surface Water Monitoring Program, accessed 12/29/09). Most of the bifenthrin detects were found in waterways located in Stanislaus County.

- Aquatic species:

Bifenthrin is highly toxic to fish and aquatic invertebrates, with a 96-hour LC_{50} from 0.00015 to 0.00035 ppm for fish and 0.0016 ppm for invertebrates. The NOEC for fish is 0.000012 ppm (EXTOXNET 1996, FOOTPRINT 2009). Bifenthrin is also of concern regarding sediment dwelling organisms (Drenner et al. 1993).

- Beneficial species:

Bifenthrin is considered highly toxic to bees, harmful to the natural enemies of pests, and moderately to highly toxic to earthworms (EXTOXNET 1996, FOOTPRINT 2009).

4.3 Chlorpyrifos

Chlorpyrifos is a widely-used organophosphate insecticide. It acts as an acetylcholinesterase inhibitor in many of the same pests as bifenthrin, and works through either ingestion or contact exposure. Chlorpyrifos is efficaciousis efficacious against pests of both orchard crops, such as peach twig borer in almonds, and field crops, such as spotted alfalfa aphid in alfalfa. It is found in products such as Govern 4E and Lorsban 4E and 15G, among others. It is available in various formulations, such as wettable and dustable powders, granules, and emulsifiable concentrates.

4.3.1 Use trends

Figure 4-6 shows the temporal use trends of chlorpyrifos in various crops for the three Central Valley watersheds between 1995 and 2006. Overall use was much higher in the dry season than in the wet season.

For all three watersheds, alfalfa and almonds were among the top five highest use commodities during both the wet and dry seasons, while walnuts were among the top five only in the dry season.

In the lower San Joaquin River watershed, walnut, cotton, corn, almond, and alfalfa had high dry season use, while apple, grapes, almond, alfalfa and peaches had high wet season use. Wet season alfalfa use and dry season cotton use appeared to be decreasing, while dry season almond use showed a recent strong increase.

Walnuts had the highest dry season use in the lower Sacramento River watershed, showing a general increase over time along with almond dry season use. Alfalfa and cotton dry season use remained low and steady over time, while sugarbeet use was discontinued after 2000. Wet season use includes dried plum, peach, corn, alfalfa, and almond, all at relatively low amounts.

The lower Delta watershed had the lowest dry season use of the three watersheds, with the top five commodities being walnuts, sugarbeets, corn, alfalfa, and almonds. Wet season use was mainly on apples, wine grapes, other grapes, almonds, and alfalfa, with alfalfa showing a significant decline in use over time (**Figure 4-6**).

Figure 4-7 shows the spatial change in the pounds of chlorpyrifos used between 1995 and 2006 for the wet and dry seasons. During the wet season, chlorpyrifos was mainly used in the Lower Delta watershed and the Lower San Joaquin River watershed, with the high-use areas clustered around Cache Creek, Putah Creek and the San Joaquin River area. Usage decreased from 1995 to 2006, especially along the San Joaquin River. During the dry season, chlorpyrifos was used along major rivers such as the Sacramento and Feather Rivers, Cache Creek, Putah Creek, and the San Joaquin River and its tributaries. Overall, use decreased from 1995 to 2006. However, new high-use areas appeared in 2006 in the northern portions of Glenn and Butte counties, and the eastern part of Madera County. Dry season use of chlorpyrifos in northern Fresno County decreased from 1995 to 2006.

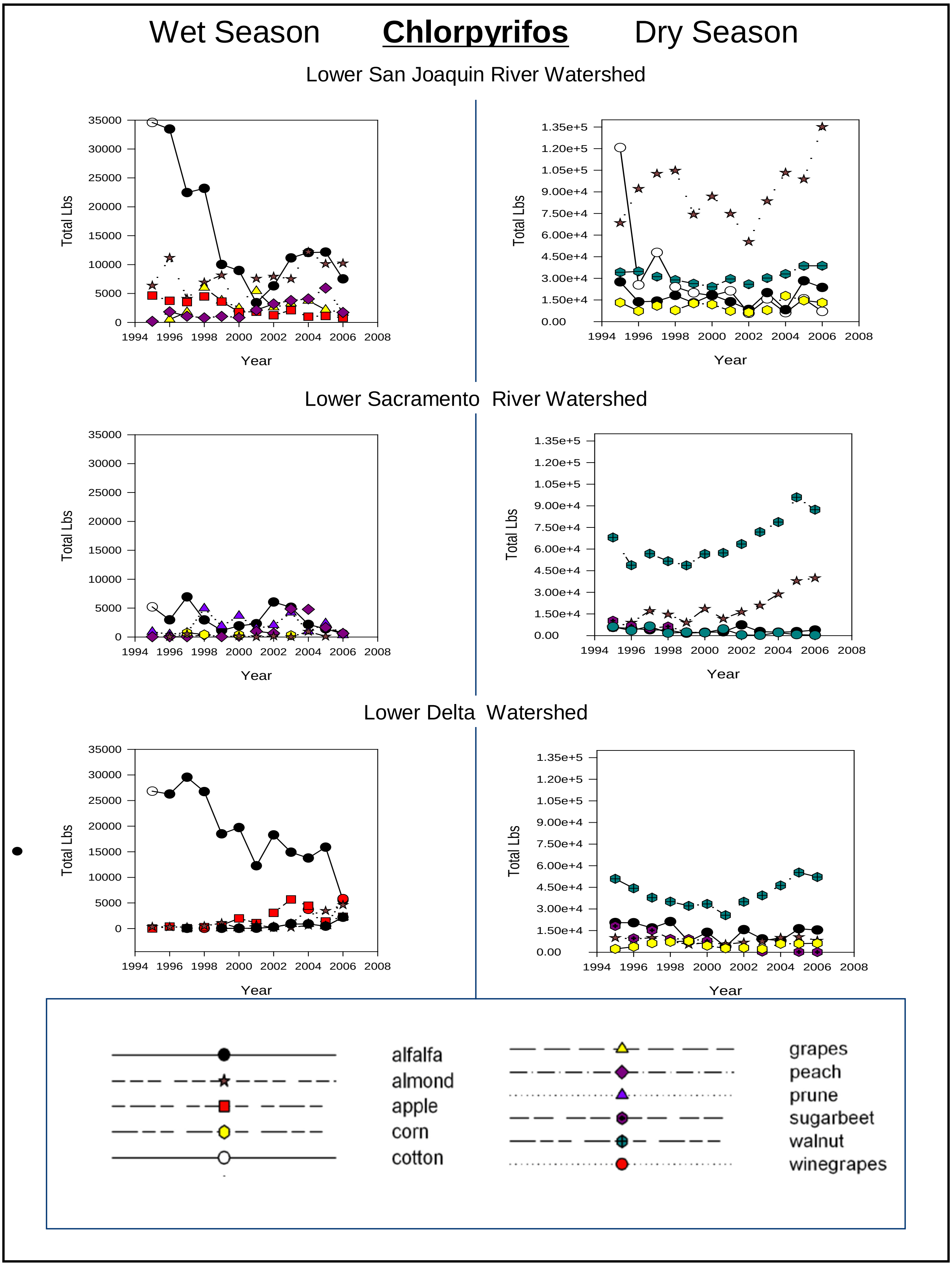


Figure 4-6 Chlorpyrifos pesticide use trends: 1995 to 2006.
Note: different Y axis scales.

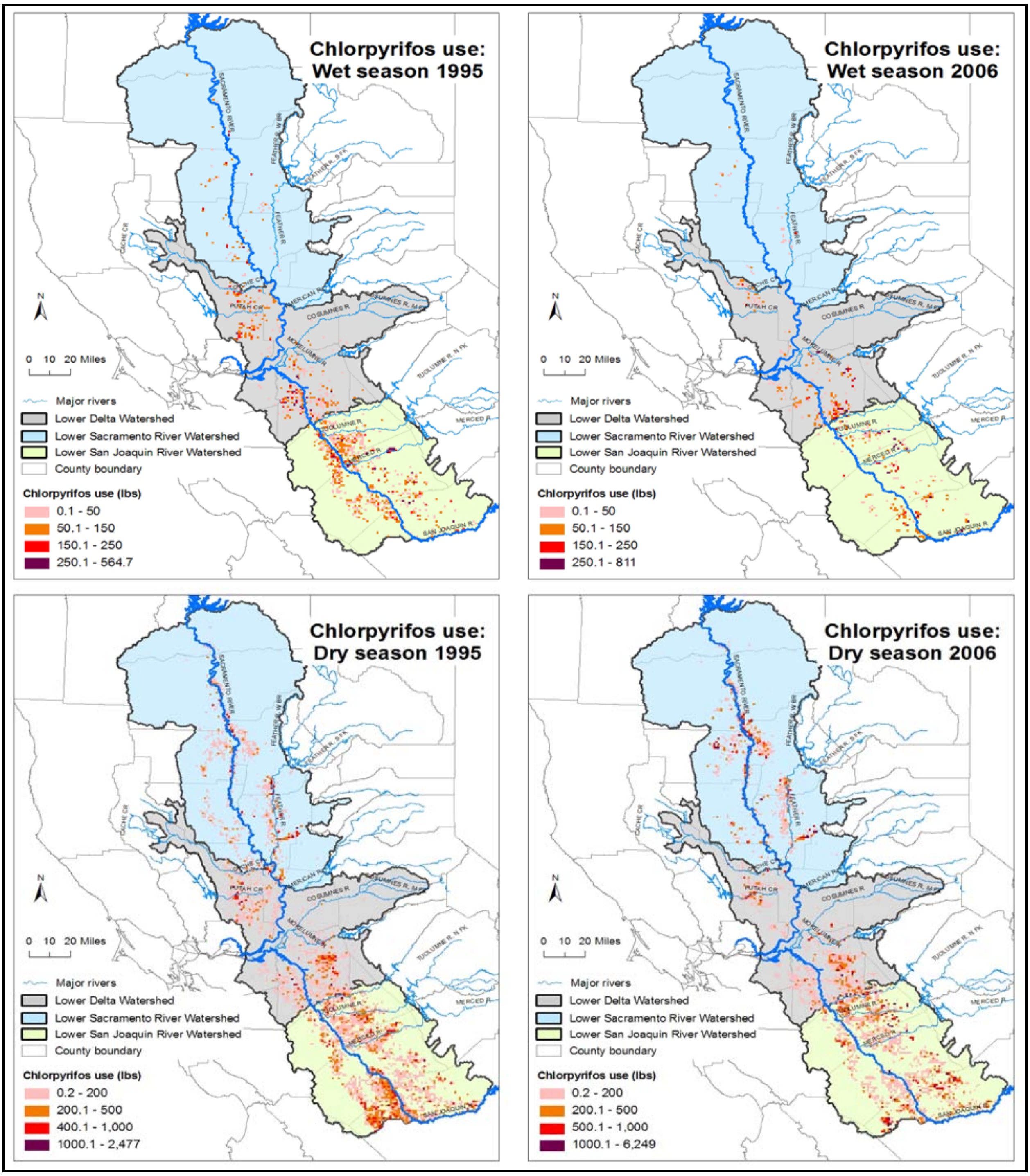


Figure 4-7 Chlorpyrifos: spatio-temporal use trend maps.

4.3.2 Toxicity and Environmental Exposure

- Water and sediment quality

Chlorpyrifos has a log K_{ow} of 4.7 (pH 7, 20^{o} C), indicating hydrophobic tendencies (FOOTPRINT 2009). Despite its hydrophobicity, it has been identified in the EPA 303(d) list as an impairment to surface water quality for 25 water bodies in California (EPA 2006a). Between 1991 and 2006 the average concentration of chlorpyrifos in surface waters of the Central Valley (CVRWQCB area) was 0.0156 ppb with a range of 0 to 2.42 ppb in water samples (CDPR Surface Water Monitoring Program, accessed 12/29/09). The highest concentrations of chlorpyrifos were found in water samples collected in Stanislaus County. Chlorpyrifos is not listed in the CDPR 6800 (a) groundwater list.

- Aquatic species

Chlorpyrifos is highly toxic to fish and aquatic invertebrates, with a 96-hour LC_{50} from 0.0013 to 0.806 ppm for fish and 0.0016 ppm for invertebrates. The NOEC for fish is 0.00014 ppm. It is also highly toxic to sediment dwelling organisms, with a 96-hour LC_{50} of 0.00002 ppm (EXTOXNET 1996, FOOTPRINT 2009).

- Beneficial species

Chlorpyrifos is considered highly toxic to bees, moderately toxic to earthworms, and demonstrates mixed toxicity to natural enemies of pests (EXTOXNET 1996, FOOTPRINT 2009).

4.4 Diazinon

Diazinon is another widely used broad spectrum organophosphate insecticide, targeting similar pests as bifenthrin and chlorpyrifos. Its non-systemic mode of action includes respiratory, ingestion, and contact toxicity. Like chlorpyrifos, diazinon is an acetylcholinesterase inhibitor. It is found in products such as Diazol AG500 and Diazinon 14G, AG500, and 15W. Formulations include granules, dust, wettable powders, seed dressings, and emulsifiable concentrates, among others.

Diazinon is efficaciousis efficacious for pests of both orchard crops, such as San Jose scale on dry plums (prunes) and row crops, such as beet armyworm on tomatoes.

4.4.1 Use trends

Figure 4-8 shows the temporal use trends of diazinon in various crops for the three Central Valley watersheds between 1995 and 2006.

In the lower San Joaquin River watershed, almonds, peaches, and dry plums were among the top five high-use crops for both the wet and dry seasons, with almonds showing decreasing use over time in both seasons and peaches showing a decreasing trend in the dry season. Apples and apricots were among the top five wet season crops, while cantaloupes and other melons were in the top five for the dry season.

In the lower Sacramento River watershed, dry plums, almonds, and tomatoes were among the top five high use commodities for both seasons. Use on dry plums and almonds showed strong decreases over time in both seasons, while tomato use was very low in the wet season, and decreased over time in the dry season. Apples and peaches were both in the top five for wet season, while walnuts and melons were in the top five for dry season, with walnuts showing a strong decrease in use over time.

Finally, in the lower Delta watershed, tomatoes, pears, and cherries were among the top five high use commodities for both seasons, while apples and almonds only exhibited high use during the wet season. Dry plums and walnuts exhibited use solely in the dry season. All commodities generally had a total use of around 10,000 pounds or less, which was a relatively low maximum range of use compared to the other two watersheds (**Figure 4-8**).

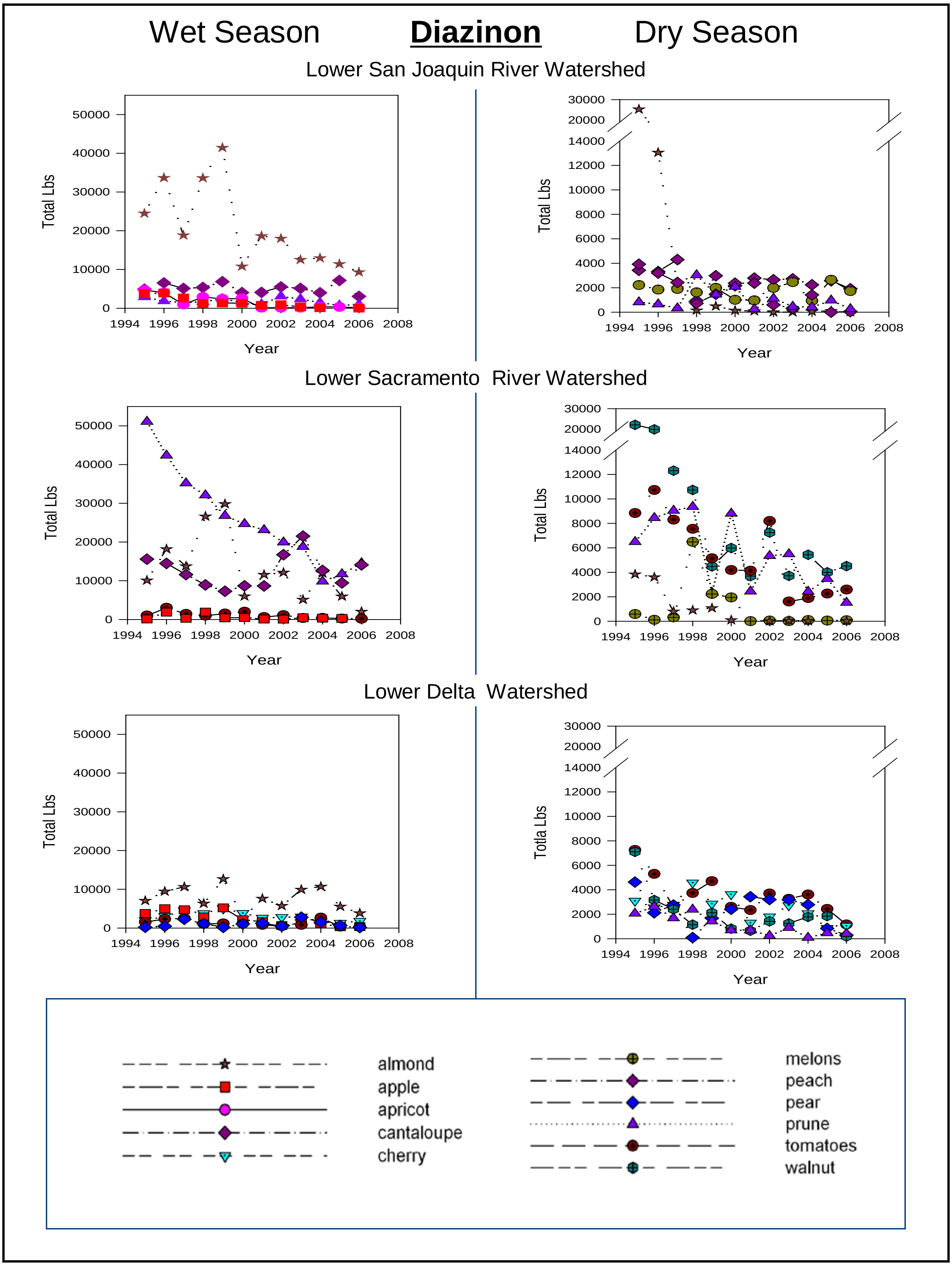


Figure 4-8. Diazinon pesticide use trends: 1995 to 2006**.**
Note different Y axis scales.

Figure 4-9 shows the spatial change in the pounds of diazinon used between 1995 and 2006 for the wet and dry seasons. Spatially, diazinon use during the wet season was high in Sutter and Yuba counties along the Feather River, as well as north and southeast of the Lower San Joaquin

River watershed. Diazinon use decreased from 1995 to 2006, especially in northern Glenn, eastern Sutter, western Yuba, and western Madera Counties. In the dry season, high diazinon use was located in the eastern portions of Yuba and Madera Counties in 1995. Diazinon use during the dry season decreased dramatically from 1995 to 2006, with considerably fewer high use areas in 2006.

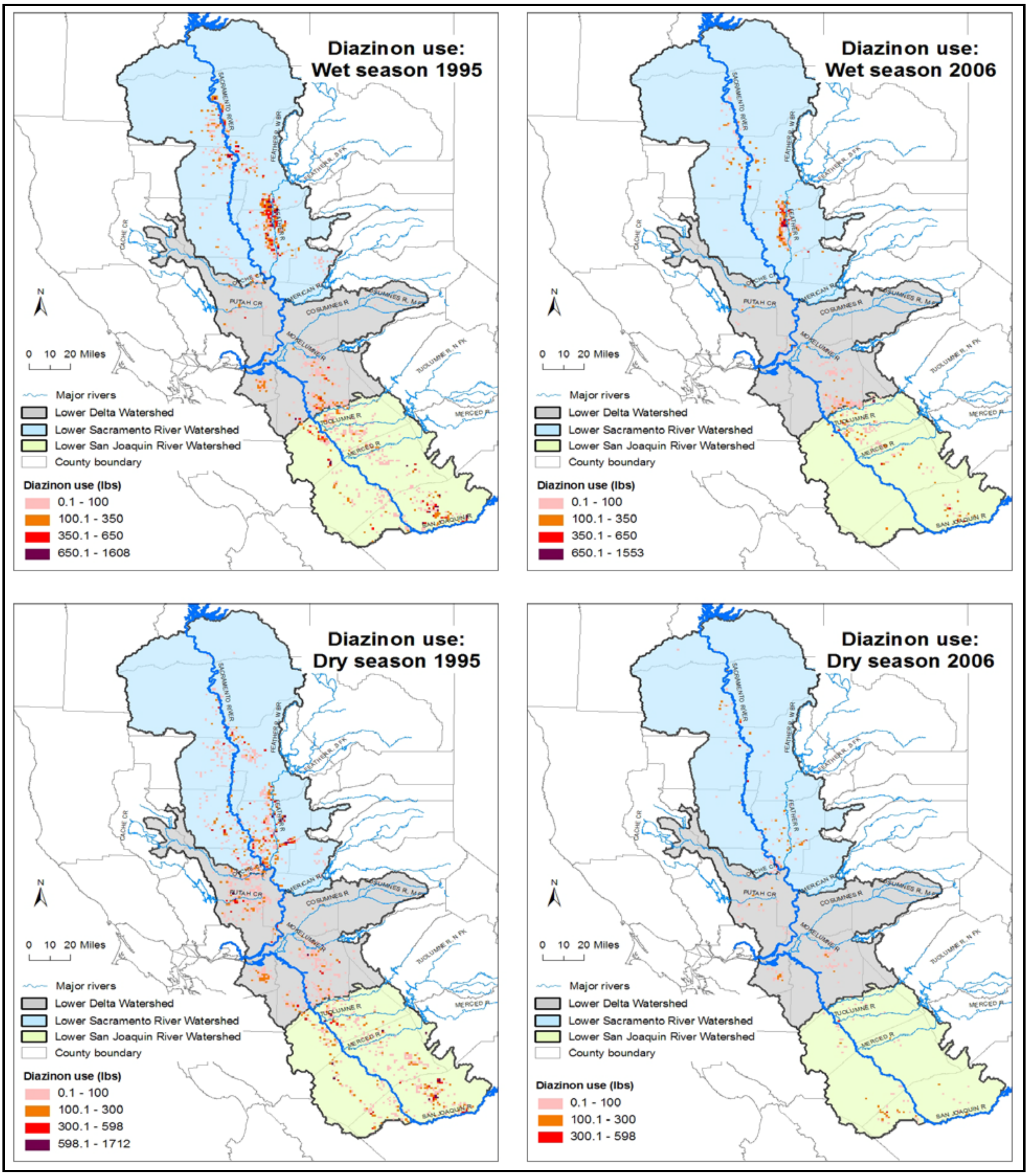


Figure 4-9 Diazinon: spatio-temporal use trend maps.

4.4.2 Toxicity and Environmental Exposure

- Water and sediment quality

Diazinon has a log K_{ow} of 3.69 (pH 7, 20^{o} C), indicating a slight hydrophobic tendency (FOOTPRINT 2009). It has been identified in the EPA 303(d) list as an impairment to surface water quality of 85 water bodies in California (EPA 2006a). Between 1991 and 2006 the average concentration of diazinon in surface waters of the Central Valley (CVRWQCB area) was 0.0926 ppb with a range of 0 to 47 ppb in surface water samples (CDPR Surface Water Monitoring Program, accessed 12/29/09). The highest concentration of diazinon was found in a water sample in Sacramento County. Detects of diazinon were prevalent in surface waters throughout the Sacramento and San Joaquin River Watersheds, but have decreased significantly in recent years. Diazinon is also listed in the CDPR 6800 groundwater list as a potential pollutant (CDPR 2007a).

- Aquatic species

Diazinon is moderately toxic to fish and highly toxic to aquatic invertebrates, with a 96-hour LC_{50} from 2.6 to 15 ppm for fish and 0.001 ppm for invertebrates. The NOEC for fish is 0.7 ppm. It is also highly toxic to sediment-dwelling organisms, with a 96-hour LC_{50} of 0.023 ppm (EXTOXNET 1996, FOOTPRINT 2009).

- Beneficial species

Diazinon is considered highly toxic to bees, moderately toxic to earthworms, and demonstrates mixed toxicity to natural enemies of pests (EXTOXNET 1996, FOOTPRINT 2009).

4.5 Malathion

Malathion is another broad spectrum, organophosphate, non-systemic, acetylcholinesterase inhibitor insecticide with contact, ingestion, and respiratory action. It is found in products such as Malathion 8 Aquamul, 8E, 8 Flowable and 5 Dust, among others. Malathion is efficacious toward pests of both orchard crops, such as walnut husk fly in walnuts, and field crops, such as alfalfa weevil in alfalfa, and targets many of the same pests as bifenthrin, chlorpyrifos, and diazinon. Malathion is also effective against pests from the order Diptera (flies).

4.5.1 Use Trends

Figure 4-10 shows the temporal use trends of malathion in various crops for the three Central Valley watersheds between 1995 and 2006.

In the lower San Joaquin River watershed, alfalfa, walnuts, grapes, succulent beans and other types of beans were the top five commodities for malathion use. Use on walnuts appeared to increase slightly over time. Wet season use was predominantly on alfalfa, with some sporadic low use on spinach, wheat, sugarbeets, and oats.

In the lower Sacramento River watershed, dry season use was mainly on alfalfa, walnuts, dried beans, wild rice, and rice in general, with use on walnuts increasing and use on rice decreasing over time. There were only four high use commodities in the watershed during the wet season: alfalfa, almond, and barley, and sporadic use on wheat.

Crops of alfalfa, walnuts, pumpkins, tomatoes, and dried beans were the five top users of malathion in the lower Delta watershed in the dry season. Again walnuts showed an increasing use trend over time. Use on pumpkins gradually declined, and tomatoes had a sharp drop off after a peak in 2002. As in the other two watersheds, alfalfa was the predominant recipient of malathion use in the wet season, with sporadic use on oats, onions, beans, and outdoor container plants (**Figure 4-10**).

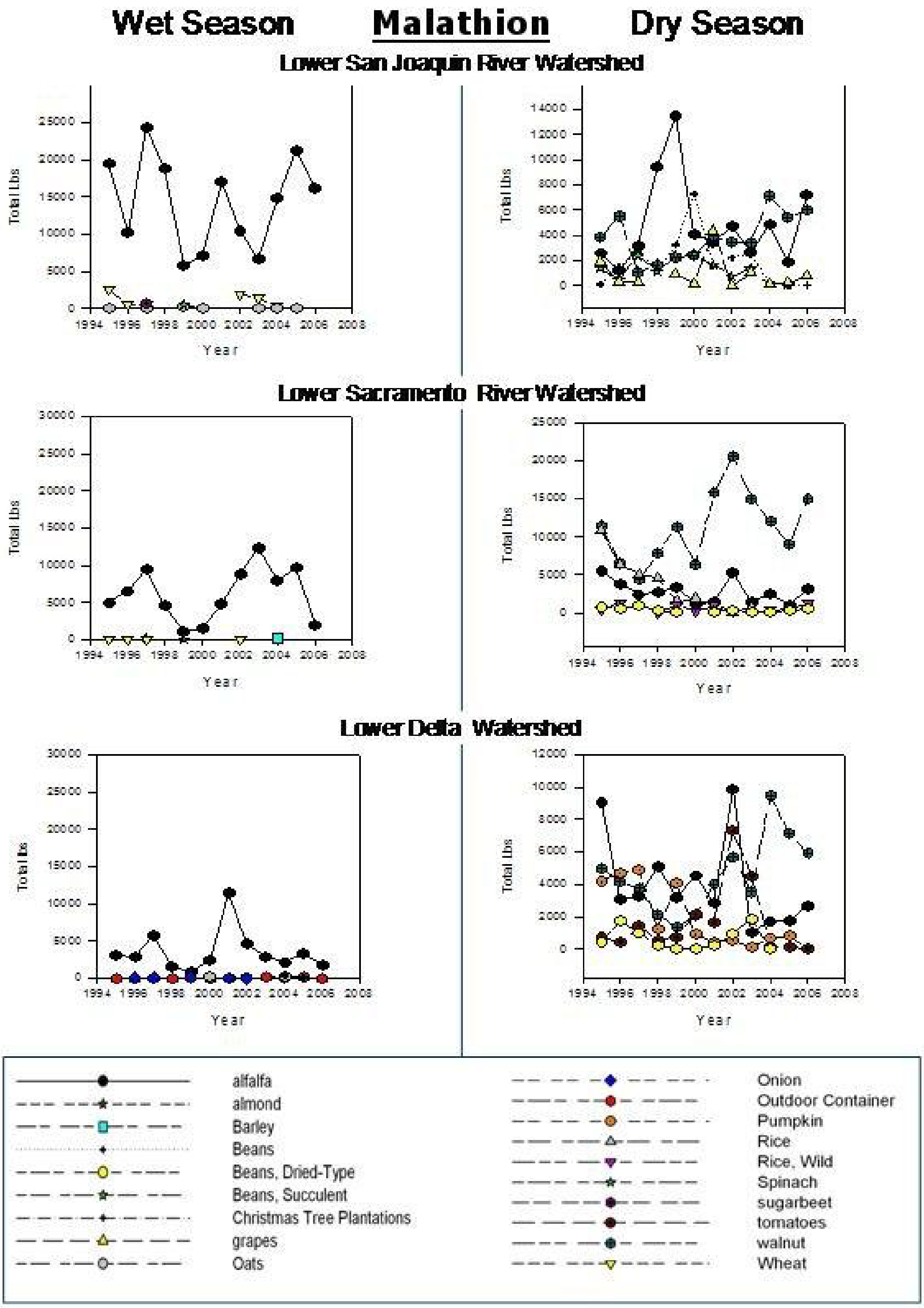


Figure 4-10 Malathion pesticide use trends: 1995 to 2006.
Note different Y axis scales.

Figure 4-11 shows the spatial change in pounds of malathion applied between 1995 and 2006 for the wet and dry seasons. Spatially, high malathion use during the wet season was found in areas in Merced County, the northeast corner of Glenn County, and the west side of Madera County. Malathion use during the wet season decreased from 1995 to 2006 in northeast Glenn County, Yolo, San Joaquin, Merced and northern Fresno counties. During the dry season, malathion was used in all three watersheds. In comparison to 1995 use of malathion, 2006 use decreased in the Lower Delta watershed in Yolo and San Joaquin counties, but increased in the Lower San Joaquin River watershed in southeast Merced County, and northern Fresno County. A few high-use spots were found in the south of Yuba County in 2006.

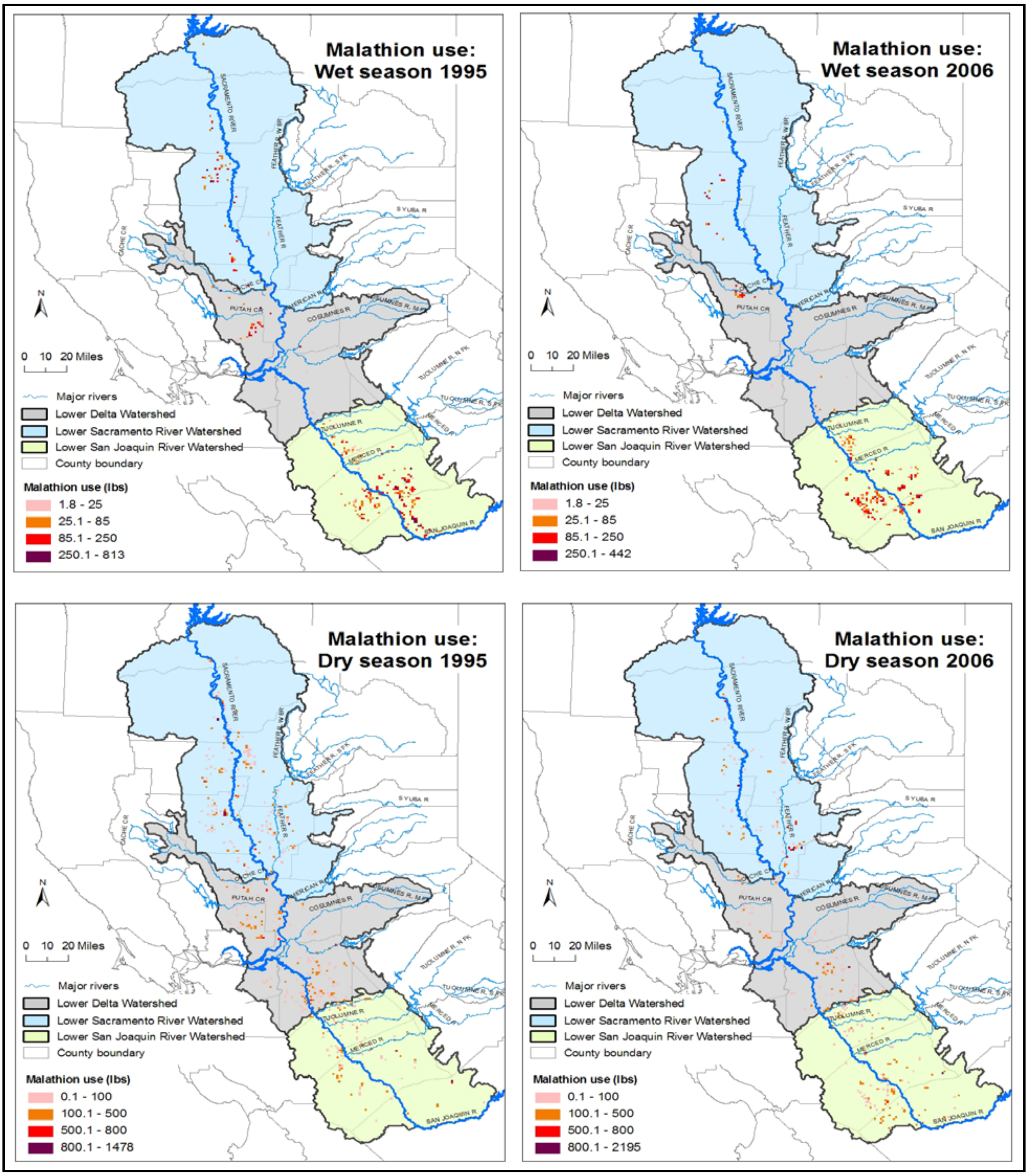


Figure 4-11 Malathion: spatio-temporal use trend maps.

4.5.2 Toxicity and Environmental Exposure

- Water and sediment quality

Malathion has a log K_{ow} of 2.75 (pH 7, 20^{o} C), indicating slightly hydrophilic tendencies (FOOTPRINT 2009). Like chlorpyrifos and diazinon, it has been identified in the EPA 303(d) list as an impairment to surface water quality in the Colusa Basin Drain, which is the single largest source of agricultural return flows to the Sacramento River (EPA 2006a). Between 1991 and 2006 the average concentration of malathion in surface waters of the Central Valley (CVRWQCB area) was 0.0058 ppb with a range of 0 to 6 ppb in water samples (CDPR Surface Water Monitoring Database, accessed 12/29/09). There was a very high detect in Sutter County (46 ppb in 2005) that was excluded from the average and range above because it appears to be an outlier. The highest concentrations of malathion were found in water samples from Colusa County. Malathion is not listed in the CDPR 6800 groundwater list.

- Toxicity to aquatic species

Malathion is moderately to highly toxic for fish and highly toxic for aquatic invertebrates, with a 96-hour LC_{50} from 0.022 to 10.7 ppm for fish and 0.0007 ppm for invertebrates. The NOEC for fish is 0.021 ppm. It is also highly toxic to sediment-dwelling organisms, with a 96-hour LC_{50} of 0.0004 ppm (EXTOXNET 1996, FOOTPRINT 2009).

- Toxicity to beneficial species

Malathion is considered highly toxic to bees, moderately toxic to earthworms, and moderately to highly toxic to natural enemies of pests (EXTOXNET 1996, FOOTPRINT 2009).

5 Available Information and Data Limitations

The data available for comparing the efficiency of preventive and mitigative BMPs was limited. For preventive BMPs, the limitations were largely due to subtle differences between the questions asked in most published studies and the questions that would need to be asked in order to determine BMP efficiency. Most scientific studies on agricultural practices with preventive BMP characteristics did not focus on the practice's ability to reduce environmental impact, but rather on its effects on community ecology questions, such as population abundance, life cycle characteristics, and/or reproductive success of the pests (or in some cases natural enemies). The results of these studies rarely reported whether the reductions in pest abundance were sufficient to replace the need for a pesticide application, and thus reduce environmental impact. Therefore, the effectiveness of those practices as BMPs often remained uncertain.

In contrast, the literature on mitigative BMPs was much more conducive to a comparative BMP efficiency analysis, as the results were often reported as percentage reductions in pollutant impact.

For both preventive and mitigative BMPs, the efficiency for reducing environmental impacts is highly site/situation specific, being largely influenced by the following three components:

- Environmental variables such as soil type, meteorological conditions, and topography;
- Farm characteristics such as commodity, pest, and community ecology; and
- Experimental aspects, such as the specific design factors of the BMPs and variation in how the experiments were conducted.

To reduce the variation in results caused by these factors, this report used results from meta-analyses and literature reviews when available, since their purpose is to synthesize the variable results of multiple studies into scientifically valid conclusions. The authors of this report conducted extensive meta-analyses and literature reviews concerning vegetative buffers, which are included in the Appendix (Liu et al. 2008, Zhang et al. 2010).

For BMPs lacking meta-analyses or comprehensive literature reviews, this report includes the results and issues presented by a subset of the existing literature, focusing on California conditions when possible. If California literature was not available, the region, commodity, and pest of the study was often noted, since results of regional commodity specific studies may not be readily transferable to other commodities, pests, or regions. Thus any conclusions should be viewed with this caveat in mind.

Costs: Acquisition of comparable economic data associated with each BMP proved very difficult to obtain. When available, data varied over the studies by year, region, commodity, and the range of information reported. Some studies supplied cost data solely pertaining to the out of pocket costs needed to implement a particular BMP, while other studies took into account all potential associated changes in the production system costs and benefits that could occur as a result of the BMP implementation. Still other studies offered net present value/cost assessments, calculating an annualized value as a result of spreading costs over the lifespan of the BMP. The level of breakdown of cost totals was not constant across all studies. Thus there are inconsistencies in the cost components that were either included or excluded from various studies for the analysis purposes of this report. While a net present value assessment of cost over the lifespan of each BMP would have been the ideal economic measure, it was beyond the scope of this report. Instead, this report supplies estimates of initial first year costs, and, when available or applicable, annual maintenance costs.

This report attempts to normalize for the variation between studies through the following methods:

- When possible, cost data from multiple studies and commodities were used, to arrive at a range of representative values

- Most values were adjusted for inflation to 2008, using an online inflation calculator, so budgets from different years could be better compared (http://www.westegg.com/inflation/infl.cgi)
- Details of cost components were recorded so that the individual components that were included or excluded from a given study are readily transparent
- Not all BMPs had costs that increased at a linear constant rate with farm acreage. Therefore, to facilitate comparisons, this report estimated the cost of a BMP needed for a 50 acre farm site, and then divided the total cost by 50 to get a cost per acre.

5.1 Methodology for Efficiency and Cost Comparisons

For the purposes of this report, the effectiveness or efficiency of a BMP was defined as its ability to reduce impact to a component(s) of the environment, such as water quality or exposure of aquatic species to a pesticide. Reductions in the percentage of pesticide runoff (dissolved in water or adsorbed to sediment), leaching, drift, VOCs, and exposure were used as proxies for reductions in environmental impact to each component. A representative or average change in cost and percentage impact reduction was calculated for every component of environmental impact with which each BMP was associated. The change in cost or impact was based on a comparison between a hypothetical farm with and without the BMP. When more than one study was analyzed, or when multiple results were reported in a given study, a range of values was reported, including the average, minimum and maximum changes in both impact and costs.

BMPs with data gaps or solely qualitative data were designated as “N/A” for comparison purposes, signifying that a quantitative comparative assessment was *not available*.

Preventive BMPs are defined as practices that reduce or eliminate the amount of pesticides needed to control pests, and thus lessen pesticide pollutant input into the ecosystem. They include a wide range of practices, such as biological control, pesticide choice, removal of pest habitat, the use of trap crops, intercropping, cover crops, attention to fertilization and irrigation efficiency, the use of resistant varieties, mulches, and the prevention of crop access by a pest through use of barriers. Multiple preventive BMPs are often implemented simultaneously, as they complement each other and thus increase overall pest control efficacy. They are also often associated with mitigative BMPs.

Quantitative data were frequently unavailable for the preventive BMPs. In some cases where there was some certainty that the BMP reduced pest pressure, it was unclear whether that reduction was sufficient to replace the need for pesticides and thus reduce environmental impact. For the preventive BMPs in particular, the potential cumulative effect when multiple preventive BMPs were practiced together was also evaluated, as this is often recommended to increase efficacy for pest control and efficiency for reducing environmental impacts. This evaluation was done under the assumption that if a preventive BMP was listed on the UC IPM website for a particular commodity and pest, then it was likely to be fairly effective. Therefore, the main limiting factor to reducing the need for pesticides was the availability of effective preventive BMPs which are also efficacious for the pests a grower would likely be targeting. The higher the efficacy of the BMP for a given pest the greater the reduction in the amount of pesticide needed to control that pest, and, therefore, the greater the reduction in pesticide inputs to surface waters. For each representative commodity, the number of pests for which a preventive BMP could replace a representative pesticide was calculated. A comparison was then made between the representative commodities to determine which were the most likely to effectively substitute representative pesticides with preventive BMPs. A comparison was also made between the various preventive BMPs to determine which had the broadest applications to multiple pests.

6 Mitigative Best Management Practices

In contrast to preventive BMPs, mitigative BMPs are defined as practices designed to decrease the environmental impact of a pesticide already applied. They include practices such as the use of buffers, windbreaks, constructed wetlands, conservation tillage, tailwater ponds, and water treatments.

6.1 Buffers

6.1.1 Definition/Background

Vegetated buffers are areas or strips of land planted with vegetation, used widely in agriculture to intercept the offsite movement of pollutants such as pesticides, sediment, and nutrients, as well as to manage wind and water path directions (Dosskey et al. 2002, Bedard-Haughn et al. 2004). Vegetated buffers improve water quality by slowing runoff and trapping pollutants.

Some common examples of buffers include contour strips, field borders/field margins, filter strips, grassed waterways, riparian buffers, and vegetated barriers, among others (**Figure 6-1**). The vegetation of the buffers provides resistance to flow which increases the residence time of the runoff on the farm, allowing both infiltration and sedimentation to increase. Water-soluble pesticides and nutrients can be captured as the runoff percolates into the soil profile. Similarly, hydrophobic pesticides and particulate nutrients can be detained by the buffer along with sediment as the runoff flow velocity and sediment transport capacity decreases.

Vegetation and soil characteristics affect residence time, trapping of particulate matter by vegetation, plant uptake and biodegradation, as well as infiltration. The surface roughness of the vegetation affects the residence time and flow velocity of the runoff, and the types of vegetation and vegetation density affect trapping and plant uptake. Vegetated waterways often have increased trapping and plant uptake relative to filter strips or other on-site buffers. Soil characteristics affect the rate of infiltration. The degree of sedimentation depends mainly on the particle size of the constituents suspended in the runoff. Almost all of the easily removable particles (larger than 40 microns in diameter) are captured within the first few meters of the filter strip (Gharabaghi et al., 2006). Large sand and silt-sized particles and soil aggregates settle from the runoff within a relatively short distance into the filter. Smaller, fine particles, such as clay, may require a longer distance to settle out.

Additional processes assist in transport or transformation of pesticides in on-site buffers. Though sedimentation is the dominant process for sediment-bound chemicals, volatilization, degradation, adsorption, and absorption are also important. For water-soluble chemicals, infiltration is complemented by adsorption onto organic matter and biodegradation.

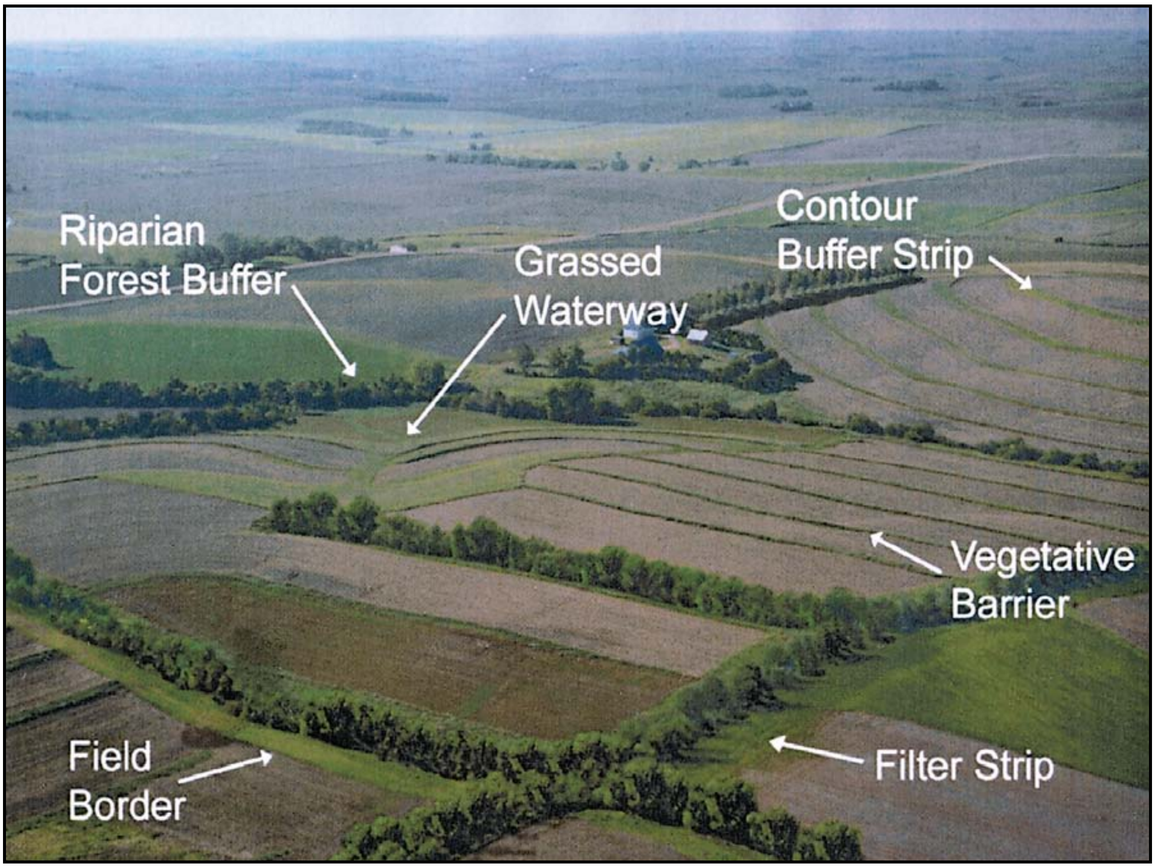


Figure 6-1 Schematic illustration of several buffer types.
Photo: USDA-NRCS (Dabney et al. 2006).

The literature uses the terms contour strips, field borders/field margins, filter strips, grassed waterways, riparian buffers, windbreaks, and hedgerows interchangeably, based on the desired effect that the buffer is intended to achieve. For example, when hedgerows are planted on the border of fields they can be termed "field borders." However, in many cases hedgerows are planted as a shelter from winds, and so are termed "windbreaks." Similarly, when vegetated filter strips are grown in waterways or water channels, they are often referred to as "grassed waterways." To clarify these terms, this report classified the various types of vegetated buffers into three groups:

1) *On-site buffers*: herbaceous or woody vegetation planted within or at the edge of the field. On-site buffers include vegetated filter strips, field borders/margins, and contour strips. The term "on-site," often referred to as "edge-of-field," not only indicates that the buffers are located on/around the farm, but also describes the mechanism of keeping pollutants on-site rather than allowing them to move off-site from the farm.

2) *Vegetated waterways*: natural waterways or ditches with herbaceous vegetation located at the perimeter of the field. Vegetated waterways include grassed waterways and vegetated ditches. Some components of constructed wetlands can also be referred to as vegetated waterways or drainages.

3) *Riparian buffers*: strips of grass, trees and/or shrubs established immediately adjacent to rivers or streams. The buffer is called a “riparian corridor” or “riparian forest buffer” if trees are the primary vegetation. Natural riparian buffers are normally forested.

Windbreaks are a kind of vegetated buffer, but because the mechanisms for their effectiveness are quite different from those of the three groups of buffers mentioned above, they are treated as a separate BMP.

One of the main differences between these three groups is the scale, both in terms of the space occupied by the buffer and the economic investment required to implement the BMP. The on-site buffer can be placed at the edge of the field or in the middle of a field, and is comparatively simple to construct. The vegetated waterways depend on a natural waterway or an irrigation ditch, and may be placed at the edge of a large block of fields. A riparian buffer may only be available on a much larger scale, and requires a significant waterway and potentially a great deal of expense either to establish or to restore a previously degraded riparian habitat.

Another difference is the location and type of vegetation and the consequent functions it performs. An on-site buffer can be composed of either herbaceous or woody vegetation. In the vegetated waterway, the vegetation's presence in the waterway itself is key to biological processes including the breakdown of pesticides and denitrification. Microbial communities and organic material play important roles in the pesticide, sediment, and nutrient reduction/conversion processes that occur in vegetated waterways and riparian buffers.

6.1.2 Effectiveness as a BMP

Mitigative effects*:*

The authors of this report conducted meta-analyses on data found in the literature regarding the effectiveness of buffers for reducing off-site movement of a multitude of agricultural pollutants, including pesticides (model based on herbicides with soil and water partition coefficients (K_{oc}) ranging from 100 to 1000), sediment, and nutrients (nitrogen and phosphorus). They reviewed 73 papers, and reported their findings in the Journal of Environmental Quality (Zhang et al. 2010). The median removal efficiency was highest for pesticides, 87.5% (and is expected to be higher for strongly hydrophobic pesticides), followed by sediment, 86%, phosphorus (P), 71.9%, and nitrogen (N), 68.3% (**Figure 6-2 and Table 6-1**). The soil type did not play a significant role in removal of sediment, N, or P, however it was not evident in the literature if soil type or soil saturation played key roles in pesticide removal.

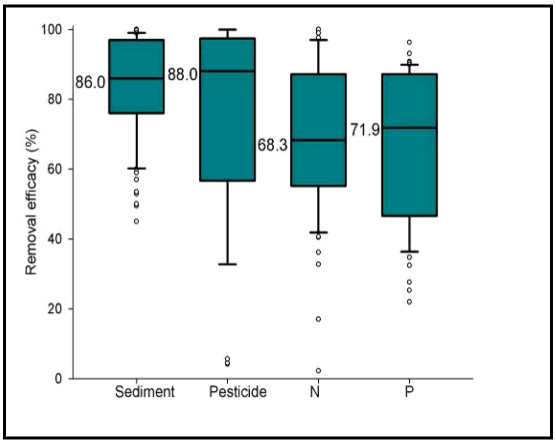


Figure 6-2. Agricultural pollutant removal efficiency of vegetated buffers. (from Zhang et al. 2010).

The efficiency of the buffer is largely dependent on the following factors (Norris 1993, Liu et al. 2008):

1) Physical properties of the buffer: width, slope, soil type, buffer to source area ratio, vegetation cover, and the structural ability of the buffer to maintain a sheet flow;

2) Timing of the runoff: if the buffer soil is saturated, the buffer is less likely to be effective as a filter;

3) Properties of the pollutant: particle size, biophysical properties of pesticides;

4) Placement of the buffer: proximity to pollutant source.

Slope, width, and vegetation*:* These four factors were included in enough studies to be evaluated in the meta-analyses performed by the authors of this report (Zhang et al. 2010). Slope and width were found to explain much of the variation in efficiency. Given that pesticides can move offsite either dissolved in runoff or attached to sediment (depending on their hydrophobicity), efficiency results will be presented for both pesticide and sediment removal. For hydrophobic pesticides buffers that have a high efficiency for sediment removal will result in a high efficiency for pesticide removal as well.

Pesticide removal from runoff: Based on the model created by Zhang et al. (2010), the authors found that a 20 to 30 meter wide buffer had the highest pesticide removal efficiency, potentially removing 92% to 93% of pesticides from the runoff (**Tables 6-1 and 6-2**). This prediction was largely based on herbicides, with the more hydrophobic organophosphates and pyrethroids expected to be removed from a combination of runoff and sediment. For pesticide runoff, buffer width explained over half of the variation in removal efficiency, while vegetation type was not a significant factor. There was not enough data to analyze the influence of buffer slope and soil type on removal of pesticides from runoff; however these factors along with the physiochemical properties of pesticides (such as K_{oc}) are likely to explain additional variation.

Sediment removal from runoff: Zhang et al. (2010) found that buffer width, slope, and vegetation type were all important factors in sediment removal efficiency, and thus removal of pesticides adsorbed to the sediment. The model predicted that 92% to 100% of sediment could be removed with a 5 to 10 m wide buffer with a slope of 10%, and vegetation consisting of either solely trees or solely grasses (that do not bend over or become submerged in the runoff), as opposed to a combination of the two together (**Table 6-1**).

Table 6-1. Predicted pollutant removal efficiency of buffers. Predictions based on width, slope, and vegetation of the buffers (Zhang et al. 2010).

		Predicted removal efficiency (%)			
	Buffer width	**5m**	**10m**	**20m**	**30m**
Sediment	(a) Slope = 5%; mixed grass and trees	67	76	78	78
	(b) Slope = 5%; grass/trees only	82	91	93	93
	(c) Slope = 10%; mixed grass and trees	77	86	88	88
	(d) Slope = 10%; grass/trees only	92	100	100	100
	(e) Slope = 15%; mixed grass and trees	58	67	68	68
	(f) Slope = 15%; grass/trees only	73	81	83	83
Nitrogen	(a) Mixed grass and trees/grass only	49	71	91	98
	(b) Trees only	63	85	100	100
Phosphorus	(a) Mixed grass and trees/grass only	51	69	97	100
	(b) Trees only	80	98	100	100
Pesticides		62	83	92	93

Table 6-2. Buffer efficiency for pesticide removal from runoff.

Pesticide AI	Pesticide Use Type or Class	Buffer Type	Buffer Width or Length (m)	% Reduction	Data Source
Atrazine	Herbicide	Vegetated Filter Strip	6	44	Patty, 1997
Atrazine	Herbicide	Riparian Buffer	7.5	52.0	Schmitt, 1999
Atrazine	Herbicide	Riparian Buffer	15	75.2	Schmitt, 1999
Atrazine	Herbicide	Vegetated Filter Strip	6	97.0	Patty, 1997
Atrazine	Herbicide	Vegetated Filter Strip	12-18	89.2	Patty, 1997
Chlorpyrifos	OP	Vegetated Ditch	Length 400	38.0	Gill et al., 2008
Chlorpyrifos	OP	Vegetated Ditch	Length 30-36	56.0	Moore et al., 2002
Deethylatrazine	Herbicide breakdown product	Vegetated Filter Strip	6	75.0	Patty, 1997
Deethylatrazine	Herbicide breakdown product	Vegetated Filter Strip	12	87.4	Patty, 1997
Deethylatrazine	Herbicide breakdown product	Vegetated Filter Strip	18	99.0	Patty, 1997
Deisopropylatrazine	Herbicide breakdown product	Vegetated Filter Strip	6	70.5	Patty, 1997
Deisopropylatrazine	Herbicide breakdown product	Vegetated Filter Strip	12	83.4	Patty, 1997
Deisopropylatrazine	Herbicide breakdown product	Vegetated Filter Strip	18	98.5	Patty, 1997
Esfenvalerate	Pyrethroid	Vegetated Ditch	Length 600	99.0	Moore et al., 2001
Fluometuron	Herbicide	Vegetated Filter Strip	0.5-1	5.1	Murphy and Shaw, 1997
Isoproturon	Herbicide	Vegetated Filter Strip	6	97.9	Vianello, 2005
Lambda Cyhalothrin	Pyrethroid	Vegetated Ditch	Length 400	25.0	Gill and Bergin, 2008
Lindane	OP	Vegetated Filter Strip	6	82.8	Patty, 1997
Lindane	OP	Vegetated Filter Strip	12	99.5	Patty, 1997

In addition to the Zhang et al. (2010) meta-analysis, the authors of this report conducted an extensive literature review analyzing the major factors influencing buffer sediment trapping capabilities. Liu et al. (2008) reviewed over 80 studies on sediment trapping by vegetative buffers, finding that a 10m wide buffer with a 9% slope was optimal, resulting in 95.17% removal efficiency. These results are consistent with **Table 6-1** from Zhang et al. (2009), which shows that from 67% to 100% of sediment can be removed with a buffer of these dimensions, depending on the vegetation used.

Source to area ratios: Source to buffer area ratio is another important factor for buffers (Misra et al. 1996). The Natural Resources Conservation Service (NRCS) set a standard for buffer width based on the Universal Soil Loss Equation (USLE) rainfall intensity (R) factor values of a region. The standard defines the ratio of the source area to the filter strip area as less than 70:1 in regions with USLE R factor values between 0-35, 60:1 in regions with USLE R factor values between 35-175, and 50:1 in regions with USLE R factor values of more than 175 (WSU 2006).

Runoff flow: The topography of the buffer can also play a role in its efficiency as a BMP. Buffers are more effective for runoff which is shallow and uniform in flow (laminar or “sheet” flow) than for runoff with concentrated flow paths. Most of the research on buffers has assumed that the flow of runoff is laminar across the buffer. However, in reality, natural berms often develop along field edges from deposition of sediment and these can create regions of concentrated flow which can dramatically reduce the effectiveness of the buffer. Attention to the maintenance of laminar flow via removal of sediment berms and the construction of barriers and vegetation to direct flow is therefore an important factor in achieving optimal BMP effectiveness (Helmers et al. 2005).

Vegetation: The height of vegetation in the on-site buffer relative to the runoff water depth is another important factor in its efficiency for reducing/preventing off-site movement of pesticides and other agricultural by-products. When the depth of runoff water moving through the filter is greater than the height of the vegetation in the filter, vegetation tends to lie over, and filtering efficiency decreases (**Figure 6-3**).

Figure 6-3 Submerged vegetation can reduce buffer efficiency.
Photo: Maryland Dept. of Natural Resources.

However, as long as submergence does not occur, vegetation height is not a significant variable in on-site buffer performance, according to a laboratory rainfall simulation experiment (Pearce et al. 1997). Comparisons of newly planted grass with well-established grass also have been undertaken. A Netherlands study found that filter strips consisting of older vegetation retained more water and reduced sediment concentration more effectively than strips vegetated with young grass (Van Dijk et al. 1996).

- Preventive effects

If vegetation is selected for the buffer that attracts natural enemies to the field or orchard, the buffer may exhibit preventive BMP characteristics through the promotion of biological control of pests. Please refer to the section on biological control for a more detailed analysis of the potential environmental benefits of preventive BMPs.

6.1.3 Representative pesticides and commodities

From the results of these two meta-analyses, it would appear that a 20m (≈ 66 feet) wide buffer with a 10% slope and either tree or grass vegetation could serve to remove an average of 96% (92% to 100%) of all pesticides, either dissolved in the runoff water, or adsorbed to sediment. If all vegetation compositions and widths of buffers are considered, as represented in **Table 6-1**, then the range expands to 58% to 100% removal of pesticide, averaging 82%.

All five representative pesticides have the potential for impacting surface water quality. The efficiency of buffers for removing pesticides in solution and adsorbed to sediment can significantly reduce the impact of the five representative pesticides to surface water. Of the five representative pesticides, bifenthrin, chlorpyrifos and diuron have a strong tendency to adsorb to sediment (high K_{oc}) and therefore buffers that have the highest efficiency for sediment removal will be most effective for removing these pesticides from runoff. In addition, if vegetation is selected to attract natural enemies, the need for pesticides could be further reduced through biological control of pests rather than chemical control.

6.1.4 Helpful links and tools

United States Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) CORE4 Conservation Practices Training Guide: The Common Sense Approach to Natural Resource Conservation, Part 4, Buffer Practices, gives in depth descriptions of different types of buffers, implementation strategies and advice (http://www.nrcs.usda.gov/technical/ecs/agronomy/core4.pdf)

Conservation Buffers, Design Guidelines for Buffers, Corridors, and Greenways, put out by the USDA National Agroforestry Center and the NRCS (http://www.unl.edu/nac/bufferguidelines/docs/conservation_buffers.pdf) (http://www.unl.edu/nac/bufferguidelines/abstract.html)

USDA National Agroforestry Center and NRCS offer an Excel-based buffer economic analysis tool that performs cost benefit analyses http://www.unl.edu/nac/buffer$.htm

NRCS Buffer Strips site: Buffer Strips: Common Sense Conservation and technical papers on individual practices (http://www.nrcs.usda.gov/FEATURE/buffers/) (http://www.nrcs.usda.gov/technical/Standards/nhcp.html)

6.1.5 Federal cost share programs and other financial incentives

Natural Resources Conservation Service (NRCS) programs: Conservation Reserve Program (CRP), Environmental Quality Incentive Program (EQIP), Wetlands Reserve Program, Wildlife Habitat Incentives Program, Conservation Stewardship Program (formerly the Conservation Security Program), the Cooperative Conservation Partnership Initiative (CCPI), and Agricultural Management Assistance (http://www.nrcs.usda.gov/programs/)

Partners for Fish and Wildlife (http://www.fws.gov/partners/)

Water quality trading guide put out by the Conservation Technology Information Center (CTIC) (http://www.conservationinformation.org/images/GPfS_FINAL.pdf)

6.1.6 Costs

The costs of buffers can be highly variable, depending on the materials and construction methods that are used. Costs for a non-engineered grassed waterway and an annually planted grassed filter strip were used to estimate a range of general buffer costs, shown in **Tables 6-3 and 6-4** (Tourte et al. 2003c, 2003d). Looking at the representative costs for a non-engineered grassed waterway, implementation in the first year ranged from $540/acre to $4,805/acre, while annual maintenance costs ranged from $540/acre to $1,612/acre. However, benefits derived from reduced costs from the protection afforded by the buffers from flood and storm related events were estimated to offset these costs by $390/acre to $1,350/acre.

In addition, if the vegetation is chosen to increase the potential of biological control of pest species, and thus reduce pesticide costs, or if the vegetation can produce a cash crop income, it may further offset costs. If the buffer takes land out of production, however, the opportunity costs presented in **Tables 6-3 and 6-4** (Tables 1-3 and 1-4) should also be taken into account. Finally, assistance from the many federal cost share programs should be considered.

For comparative purposes, the grass filter strip was estimated to be the length of a square 50 acre field, with the 20 meter width recommended by the meta-analysis. It would therefore be 1475 feet long and 65 feet wide, or 95,875 square feet (2.2 acres). The installation cost would range from $436/acre to $10,542/acre, resulting in a total cost of $959 to $10,546 for the 2.2 acre buffer. When the cost is distributed across the entire 50 acres being served by the BMP the cost of the BMP is only $19/acre to $211/acre (average: $115/acre). After the installation year, annual maintenance costs range from $19/acre to $77/acre (average $48/acre). In terms of changes in cost between a hypothetical farm with and without a buffer, these cost estimates should be viewed as increases in costs compared to a field without a buffer, holding all other production costs constant.

Table 6-3. Buffer cost estimate: installation and maintenance of a grassed waterway. From U.C. Cooperative Extension, Central Coast Conservation Practices for a non-engineered grassed waterway (a 1000 linear feet, 10 foot width, 4 foot depth) (Tourte et al. 2003d).

Costs per unit[a]	Low	Representative	High
Installation Costs (Year 1)			
Clean waterway and smooth banks	$0	$643	$1,542
Plant erosion control mix	$0	$48	$67
Set up sprinklers and irrigate	$0	$63	$114
Installation Costs - Subtotal	$0	$754	$1,724
Annual Operation & Maintenance (Years 2-5):			
Mow vegetation (hand)	$31	$63	$125
Clean waterway	$0	$322	$771
Annual Operating and Maintenance Costs - Subtotal	$31	$384	$896
Interest on Operating Capital @ 7.4%	$1	$7	$8
First Year Costs	$33	$1,145	$2,628
Reduced Costs associated with flood control and storm events	$0	$322	$771
First Year Costs minus flood/storm benefits	**$33**	**$823**	**$1,857**

[a]Costs adjusted for inflation to reflect probable 2008 costs (http://www.westegg.com/inflation/)

Table 6-4. Buffer cost estimate: installation and maintenance of a grassed filter strip. From U.C. Cooperative Extension, Central Coast Conservation Practices for an annually planted grassed filter strip (a 1,300 linear feet, 16 foot width) (Tourte et al. 2003c).

Costs per unit[a]	Low	Representative	High
Annual Installation, Operation & Maintenance			
Site prep - disc	$9	$29	$38
Spot spray - herbicide	$10	$21	$29
Plant filter strip	$0	$25	$252
Set up sprinklers and irrigate	$0	$44	$64
Mulch-straw	$0	$124	$204
Mow vegetation (machine)	$9	$20	$28
Hand weed	$0	Not available	$47
Annual Installation, Operation & Maintenance - subtotal	$29	$263	$663
Interest on Operating Capital @ 7.4%	$1	$6	$15
Costs	$30	$268	$678
Reduced Costs associated with flood control and storm events	$0	$193	$257
First Year Costs minus flood/storm benefits	**$30**	**$75**	**$420**

[a] Costs adjusted for inflation to reflect probable 2008 costs (http://www.westegg.com/inflation/)

6.2 Windbreaks

6.2.1 Definition/Background

A windbreak can be defined as a wall of vegetation with the function of preventing the wind, and therefore pesticide drift, from moving across the vegetation at full velocity and concentration (Ucar and Hall 2001). They also reduce erosion by reducing wind speed. Windbreaks normally consist of a row or rows of trees, shrubs and/or other plants, located along crop field borders or within the field. There are two main mechanisms behind the ability of windbreaks to mitigate pesticide spray drift: deposition of spray droplets on the structure of the windbreak and distortion of the wind velocity profile as air passes over and through the windbreak. The porosity of the windbreak, the vegetation height, and the width of the windbreak are the most important factors influencing its efficiency as a BMP for reducing/preventing off-site movement of pesticides.

6.2.2 Effectiveness as a BMP

- Mitigative

Ucar and Hall (2001) reported that many studies in New Zealand and the Netherlands have documented spray drift reductions of 80-90% through the use of windbreaks, although there is still uncertainty about the primary influential factors on efficiency. A study by Brown et al. (2004) in Ontario, Canada found that a vegetated 10m-wide field margin with a dense windbreak (25% porosity) provided adequate protection to an adjacent wetland under high winds (>4 m/s). Thistle et al. (2007) conducted a study in Oregon on the spray drift reduction of a riparian windbreak buffer and found 58-96% reduction in fine droplet spray.

- Factors affecting BMP efficiency:

Needle-like foliage captured two to four times more spray than broad-leaved vegetation in a wind tunnel experiment performed by Ucar et al. (2003).

Porosity, defined as the ratio or percentage of open space to the space occupied by tree stems, branches, twigs and leaves, is important because it affects the degree of wind speed reduction as well as the shelter extent behind the windbreak (Naegeli 1953, Raine and Stevenson 1977). The optimum aerodynamic porosity is usually considered to be 35-45% (Jensen 1954, Hagen and Skidmore 1971a, b, Raine and Stevenson 1977).

Variation in individual tree height in the windbreak may also influence windbreak effectiveness. Large gaps in the windbreak's upper profile will cause additional turbulence which may shorten the shelter extent of the windbreak. Klingbeil et al. (1982) found that wind speed reduction was affected if gap depth exceeded approximately one-tenth of total windbreak height.

Finally, the width of the windbreak is also an important factor. Simulations have shown that the width controls the permeability of the windbreak and that as the width increases, the absolute pressure perturbation decreases significantly. The width of the windbreak also determines the patterns of the wind speed inside the windbreak, including the location of minimum wind speed (Wang and Takle 1996). Thus, width affects how well the windbreak can disrupt the airflow pattern and reduce wind speed across the fields in order to decrease the potential for off-site movement of pesticides (Ucar and Hall 2001).

- Preventive effects

As described in the buffer section, if vegetation that attracts natural enemies to the field or orchard is selected for the windbreak, the buffer may exhibit preventive BMP characteristics through the promotion of biological control. Please refer to the section on biological control for a more detailed analysis of the potential environmental benefits of preventive BMPs.

6.2.3 Representative pesticides and commodities

If implemented effectively, a windbreak could substantially reduce offsite movement in spray drift of all representative pesticides. Citing the study with the highest variation as a conservative estimate, it appears drift could be reduced from 58% to 96%, with an average reduction of 77%. Depending on the location of the windbreak and application practices, the exposure of surface water and aquatic species to pesticides could be reduced significantly. In addition, if biological control is improved due to the vegetation selection for the windbreak, pesticide use could be decreased.

6.2.4 Helpful links and tools

Please see buffer section.

6.2.5 Costs

The cost of windbreak installation and maintenance was estimated using the cost of a typical hedgerow, as described by UCCE in **Table 6-5**. A 1000 linear foot hedgerow (width 8 ft) would cost around $2,761 ($0.34/square foot or $14,921/acre) for installation and $602 ($0.07 per square foot or $3,165/acre) for annual maintenance (costs adjusted for inflation to reflect 2008). The National Resource Conservation Service (NRCS) estimated windbreak costs at $1 to $3 per linear foot, for one to three rows of trees and shrubs, respectively (NRCS 2007).

Many of the federal cost share programs and financial incentives listed under the buffer tools section can also be used for windbreak establishment.

In order to compare BMPs, a cost was calculated for a hypothetical windbreak, estimated to be 95,875 square feet for a typical 50 acre farm, following the dimensions described for a typical buffer. Installation costs were estimated to be $14,921/acre ($0.34/ square foot), with annual maintenance costs of $3,165 ($0.07/square foot). Distributing the cost of a 95,875 square foot windbreak over the 50 acres being served by the BMP resulted in estimates of $652/acre for installation and $134/acre for maintenance costs. No range was available.

In terms of changes in cost between a hypothetical farm with and without a windbreak, these cost estimates should be viewed as increases in costs compared to a field without a windbreak, holding all other production costs constant.

Table 6-5. University of California Cooperative Extension (UCCE) Estimated costs for a perennial hedgerow planting.
Tourte et al. 2003a.

Costs per unit[a]	**Low**	**Representative**	**High**
Installation (Year 1):		$	
Land Prep - Rip	0	25	48
Land Prep - Disc	0	17	25
Compost Application	0	33	64
Set Up Irrigation System & Pre-irrigate	25	603	781
Plant Perennial Shrubs	1,116	1,950	2,588
Irrigate to Establish	0	7	7
Mulch Around Plants	0	128	160
Installation Costs - Subtotal	1,141	2,761	3,672
Annual Operation & Maintenance (Years 2-5):	0	0	0
Irrigate to Maintain	25	20	20
Replant to Maintain	86	164	211
Hand Weed Around Plants	157	313	470
Rodent Control - Trap	59	105	164
Annual Operating and Maintenance Costs	327	602	864
Interest on Operating Capital @ 7.4%	24	47	65
First Year Costs	1,491	3,410	4,601

[a] Unit: 1,000 linear feet
Costs adjusted for inflation to reflect probable 2008 costs (http://www.westegg.com/inflation/)

6.3 Constructed Wetlands and Tailwater Ponds

6.3.1 Definition/Background

Tailwater is the water that exits the lower end of a field as part of common irrigation practices such as furrow or border strip irrigation. This runoff is necessary to ensure adequate distribution and infiltration over the entire field. Tailwater ponds are a type of collection system for the runoff water (**Figure 6-4**), most often used in row and field crop systems rather than orchard and vine crops. They are usually designed with irrigation volumes in mind, and hence are not a practical solution for higher runoff volumes that can be associated with winter rains (Schwankl et al. 2007b, c).

Figure 6-4 Tailwater pond at field corner.
Photo: Yolo County RCD, Capay Valley Conservation and Restoration Manual.

The water collected in a lined tailwater pond is prevented from entering surface or groundwater, and can be re-used if the grower establishes a return system to pump or direct the water back into the irrigation system. However, if the concentration of pesticides, nutrients, or other pollutants becomes high, the water may need to be filtered prior to re-use. Hence, tailwater ponds can be vegetated, serving as a type of constructed wetland, in order to filter the water for re-use or for return to surface or groundwater supplies.

Within agro-ecosystems, constructed wetlands can not only remove pollutants from agricultural runoff but also provide various ecosystem services, such as preserving or restoring the natural balance between surface waters and groundwater, and providing additional wildlife habitat.

Constructed wetlands are generally smaller in size than natural wetlands: approximately 60% are less than 10 hectares. There are two main types of constructed wetlands: free water surface and vegetated submerged beds. The water depth in free water surface systems is generally shallow, less than 300mm, to encourage plant growth. They appear similar to natural wetlands, with aquatic plants rooted in soil on the wetland bottom, and water flowing through the leaves and stems. Vegetated submerged beds, or subsurface flow wetlands, do not have standing water, but have plants rooted in beds of soil or gravel through which the runoff water flows, often beneath the surface. The water is therefore filtered through the roots and rhizomes, rather than the stems and leaves (Lin and Lee 2007).

In a typical constructed wetland, as described by Higgins et al. (1993), runoff water from agricultural land first enters the sediment basin where large particles settle out of the water column. Once the basin fills, the overflow enters a level lip spreader which evenly distributes the runoff across the width of the filter strip, thereby obtaining sheet flow across the grass filter strip. The water then enters the wetland, within which the vegetation further slows flow, allowing more particles to settle, capturing nutrients and pesticides. Finally, the water enters the detention pond, which allows further time for smaller particles to settle out of the water. Additionally, the longer the time that the runoff remains in the system, the more microbial communities can break down the pesticides.

The sequence of each component of the constructed wetland was carefully considered for the purpose of maximizing the effectiveness of the entire system. By first removing larger particles, the sedimentation basin reduces the impact of erosion on downstream components and increases the effectiveness of the grass filter strip. The grass filter strip is placed ahead of the wetland pond to reduce the negative impact of pollutants on wetland vegetation, given the assumption that replacing the grass would be easier than replacing the wetland vegetation and microbial communities in the aquatic system.

Vegetation:

The primary benefits of vegetation in wetlands and tailwater ponds are its ability to reduce organic and suspended solids in the water via storage of nutrients in its biomass, and its role as a filter which increases sedimentation. Another benefit is that the plant and associated litter layer provides natural habitat for beneficial microbial organisms, which contribute to further biochemical breakdown processes (Luckeydoo et al. 2002). In particular, macrophytes filter the water by adsorbing pollutants in biofilms before it flows into other vegetation in the wetland (Kadlec and Knight 1996). Sediment characteristics, plant tolerance to the pollutant, and the chemical characteristics of the pollutant itself all govern the capability of plants to process contaminants (Zablotowicz and Hoagland 1999). A field study conducted in South Africa (Schulz et al. 2003a) examined the mechanisms of azinphos-methyl sorption by constructed wetlands. The authors concluded that, given the available data, it was not possible to determine whether the vegetation itself or the microbial communities attached to the plant surface were responsible for the azinphos-methyl sorption within the wetland.

6.3.2 Effectiveness as a BMP

- ## Mitigative

Constructed wetlands and vegetated tailwater ponds can be very effective for removing pollutants such as sediment, nutrients, and pesticides from agricultural waste water. **Table 6-6** summarizes their effectiveness to treat runoff for sediment, nutrients, and various pesticides.

Table 6-6. BMP effectiveness for pesticide and sediment removal: constructed wetlands/vegetated tailwater ponds.

Pollutant	**Effectiveness/Contaminant Reduction**	**Source**
Sediment	73-100%	Higgins et al. 1993
Nitrogen	>50%	Brix 1994; Braskerud et al. 2005; Higgins et al. 1993
Phosphorus	1-100%	Brix 1994; Braskerud et al. 2005; Higgins et al. 1993
Atrazine (herbicide)	17-42% (mass)	Moore et al. 2000
Metolachlor (herbicide)	99%	Moore et al. 2001a
Atrazine (herbicide)	99%	Moore et al. 2001b
Azinphos-methyl, Chlorpyrifos, Endosulfan	89% reduction in toxicity	Schulz et al. 2004
Chlorpyrifos (OP)	47-65%	Moore et al. 2002
Methyl parathion (OP)	95% reduction in toxicity	Schulz et al. 2003a
Azinphos-Methyl (OP)	90±1% 61±5% AZP mass retention	Schulz et al. 2003b
Methyl parathion (OP)	90%[a] reduction in toxicity	Milam et al. 2004

[a] reduction in acute toxicity to *C. dubia* and *H. azteca* with 10-day residence time; reduction in acute toxicity to *H. azteca* with 44m of vegetated and 111m of non-vegetated wetland

Recent studies from around the US have shown the importance of aquatic vegetation for mitigation of pesticide influx through wetlands and agricultural drainage ditches (Moore et al. 2001a, Schulz et al. 2003b, c, Bennett et al. 2005). For example, the travel distance required for runoff to reach a given level of methyl parathion concentration reduction for a non-vegetated wetland was 3.35 times greater than that of a vegetated wetland (Moore et al. 2006). The effective size of the wetland is therefore dependent upon the pollutant as well as whether the wetland is vegetated. Studies by Moore et al. (2001a, b) found that 100-400m of travel distance should be sufficient to reduce metolachlor concentration by 99%, while 100-280m was required for the same percent reduction in atrazine. These results demonstrate that the optimal size of the constructed wetland varies depending on the targeted pollutants and site characteristics.

One important consideration in the construction of the wetlands or tailwater ponds is the use of a liner sufficient to prevent groundwater contamination. Storage or filtering of pesticide laden water can result in leaching through the soil profile if a liner is not present.

6.3.3 Representative pesticides and commodities

If implemented correctly, lined constructed wetlands and vegetated tailwater ponds could serve to reduce or eliminate negative surface impacts from all representative pesticides in all representative commodities. From **Table 6-6**, we can estimate a range from 17% to 99% reduction in OPs and herbicides in runoff. No data on the effectiveness of constructed wetlands and vegetated tailwater ponds for pyrethroid removal was obtained, but the high efficiency of these BMPs for sediment removal and removal of other pesticides indicates that pyrethroids would also be effectively removed. Groundwater impacts can also be prevented as long as water is stored above a liner.

6.3.4 Helpful links and tools

The EPA has an online manual for constructed wetlands for treatment of municipal wastewaters
(http://www.epa.gov/owow/wetlands/pdf/Design_Manual2000.pdf)

The California Stormwater Quality Association has a chapter on constructed wetlands in their Industrial and Commercial BMP handbook.
(http://www.cabmphandbooks.com/Documents/Industrial/TC-21.pdf)

The Coalition for Urban/Rural Environmental Stewardship (CURES) offers a manual on constructed wetlands
(http://www.curesworks.org/bmp/WetlandsDesignGuide.pdf)

Yolo County Resource Conservation District (RCD) puts out a manual with guidelines for tailwater ponds, among many other BMPs
(http://yolorcd.org/resources/manuals/Revised%20Manual%20111702.pdf)

6.3.5 Costs

Constructed wetlands and tailwater return systems tend to have high initial costs due to the large amount of excavation, construction, and engineering required. Construction costs will vary substantially depending on the type of liner, plants, local geological conditions that may hamper excavation and construction, and shipping costs for materials.

Table 6-7 shows estimated costs for a constructed wetland with liner and **Table 6-8** has costs for a tailwater return system serving around 700 acres of agricultural land. Total costs ranged from around $254,000 to $378,000 for the one acre wetland (NRMRL 2000, CASQA 2003). For the large tailwater system (i.e. community or regional level system), costs were estimated at around $335,000 with annual maintenance costs of around $6000 (CURES 2007). If we assume that these systems serve approximately 700 acres of agricultural fields, then installation costs per acre range from around $360 to $480 per acre, with annual maintenance costs around $9 per acre.

CURES provided estimates for smaller tailwater return systems, ranging from 1.5 to 4 acre feet capacity, that are more likely to be implemented on individual farms rather than regionally (**Tables 6-9 and 6-10**). Installation costs ranged from around $18,000 to $37,000, or $9000 to $12,000 per acre-foot capacity. Annual maintenance costs ranged from $250 to $762, or $167 to $191 per acre-foot capacity (CURES 2007).

Federal cost share programs, listed in the buffers section, should also be considered for constructed wetlands.

For BMP comparative purposes, a tailwater pond with a 1.5 acre-foot capacity was estimated to be sufficient for a 50-acre field. Installation costs ranged from around $9,000 to $12,000 per acre-foot, and maintenance costs ranged from around $170 to $190 per acre-foot. Dividing total costs for a 1.5 acre-foot capacity tailwater return system by 50 acres resulted in a range of installation cost from $273 to $363 per acre, and a range of annual maintenance costs from $5 to $6 per acre. Larger tailwater systems and constructed wetlands serving acreages at regional levels were estimated to run from around $360 to $480 per acre, with maintenance costs at around $9 per acre. Averaged together, installation costs ranged from $273 to $479 per acre (average $352 per acre), and maintenance costs ranged from $5 to $9 per acre (average $7 per acre).

These cost estimates should be viewed as increases in costs compared to a field without a tailwater system or wetland, holding all other production costs constant.

Table 6-7. Costs for a one-acre constructed wetland with membrane liner.
Cost data source: NRMRL 2000, maintenance estimates source: CASQA 2003

Input	Costs ($) / Acre			
	Vegetated Submerged		**Free Water Surface**	
	Low	*High*	*Low*	*High*
Survey/geotechnical	1,496	2,992	1,496	2,992
Clearing, Vegetation Removal[a]	2,720	6,799	2,720	6,799
Excavation and Compaction[b]	9,926	16,453	9,926	16,453
Membrane Liner[c]				
30 mil PVC	20,805	23,796	20,805	23,796
40 mil PE	23,796	26,652	23,796	26,652
40 mil PPE	29,643	32,635	29,643	32,635
45 mil Reinforced PPE	35,490	38,482	35,490	38,482
60 mil Hypalon	38,482	44,465	38,482	44,465
XR-5	56,295	62,278	56,295	62,278
Media[d]	71,252	109,733	8,839	11,014
Plants, Planting[e]	4,759	9,518	4,759	9,518
Control Structures	2,720	8,839	21,756	21,791
Plumbing, Fencing	9,518	9,518	9,518	9,518
Total	306,900	392,157	263,524	306,391

[a] costs will be higher in areas with large trees, [b] usually \$2.50 to \$4.00/m^3, [c] For rocky soils, costs are an additional \$2700 to \$4300 per acre, [d] costs will be higher if farther from gravel source, [e] \$0.75-1.25 per plant
Note: Costs adjusted for inflation to reflect probable 2008 costs (http://www.westegg.com/inflation/)

Table 6-8. BMP costs: contractor designed and installed tailwater return system.
Costs based on 600 acre feet of runoff from 700 acres of irrigated alfalfa, walnut, and dry bean fields in Hanford CA (CURES 2007)

Item	Cost ($)
Design	40,982
Construction	306,794
Total	347,776
Annual Pumping Costs	6,562

600 acre feet at 10 AF for electricity
Note: Costs adjusted for inflation to reflect probable 2008 costs (http://www.westegg.com/inflation/)

Table 6-9. BMP costs: tailwater return pond for individual growers.
Estimates for 1.5 (low) and 4 (high) acre feet capacity wildlife friendly ponds (CURES 2007).

	Cost ($)	
Installation	**Low (2,500 yd^3)**	**High (7,500 yd^3)**
Pond	4,776	14,758
Return System	12,614	20,528
Vegetation Establishment	1,435	3,637
Total	18,824	38,924
Annual Maintenance	259	791

Costs adjusted for inflation to reflect probable 2008 costs (http://www.westegg.com/inflation/)

Table 6-10. BMP costs: tailwater return pond.
Estimates for 1.5 (low) and 4 (high) acre feet capacity ponds (CURES 2007)

	Cost ($)	
Installation	**Low (2,500 yd^3)**	**High (7,500 yd^3)**
Pond and inlet/outlet structures	4,877	14,628
Return System w/ 1800' pipe	12,190	19,504
Addition of native vegetation	1,219	3,657
Total	18,285	37,789

Note: Costs adjusted for inflation to reflect probable 2008 costs (http://www.westegg.com/inflation/)

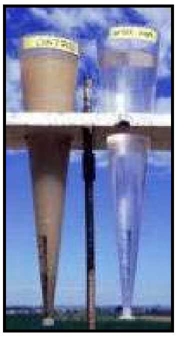
6.4 Water Treatments

6.4.1 Definition/Background

Water treatments can be used to remove sediment or pesticides in runoff before it is transported offsite. Two promising treatments are polyacrylamide (PAM) and Landguard™. PAM is a synthetic polymer that binds small soil particles together to form larger particles. Therefore, it stabilizes the soil structure, increases infiltration, and flocculates suspended sediment (**Figure 6-5**). PAM can be applied via surface and sprinkler irrigation or to tailwater runoff, to reduce off-site movement of sediment-bound pesticides.

Landguard™ is an enzyme that can be applied to irrigation water and runoff to quickly break down certain organophosphate pesticides, thus reducing their toxicity and half-life. Currently Landguard OP-A is available for sale and use in the US to deactivate organophosphates. Similar products that work on other classes of pesticides, such as pyrethroids, are in development.

Runoff from irrigation furrow.



Runoff from irrigation furrow treated with PAM.

Figure 6-5 PAM sedimentation.
Photo: http://www.nwisrl.ars.usda.gov/research/PAM

6.4.2 Effectiveness as a BMP

PAM: PAM has been shown in numerous studies to reduce soil erosion through increased infiltration in conventional surface flow irrigation (Trout et al. 1995, Sojka et al. 1998a, b, Lentz et al. 2001). Reductions in sediment loss can reduce the amount of pesticide moving offsite following adsorption to sediment particles. Many surface irrigation studies have shown reductions in sediment loss of 94% on average, ranging from 80 to 99% (Evans 2009). Lentz et al. (1992) reported that at low flow rates (10g m^{-3}), PAM reduced mean sediment load by 97% compared with untreated control furrows in bean fields in Idaho. Lentz et al. (1994) reported a reduction in sediment loss by 94% and increased net infiltration by 15%, concluding that PAM is most effective at rates greater than 0.7 kg ha^{-1}. Results similar to those from surface irrigation studies have been shown with sprinkler studies, though percentage reductions in sediment loss are generally less (Evans 2009). In a sprinkler irrigation laboratory experiment, Aase et al. (1998) found that soil loss was reduced by 75% compared to the control, when using PAM at a 2 kg ha^{-1} rate. The reduction in erosion has been shown to reduce transport of adsorbed pesticides offsite from fields (Agassi et al. 1995, Bahr and Steiber 1996, Bahr et al. 1996, Singh et al. 1996).

Landguard™: Landguard™ is a relatively new product, and thus few scientific studieson its effectiveness have been published. A project report by Markle and Pritchard (2008) of the Coalition for Urban/Rural Environmental Stewardship (CURES), found that diazinon runoff from dried plums in Chico, California, could be reduced by 16% to 99% at a low Landguard application rate of 0.00005g/l, and 93% to 100% with a high rate of 0.00010 g/l. In another technical report on Landguard, tests with alfalfa tailwater found that when the Landguard was applied in a vegetated drainage ditch, it degraded 70% of chlorpyrifos within the first 6 minutes, and 100% after 18-20 minutes (Markle 2007).

6.4.3 Representative pesticides and commodities

Currently, PAM looks promising for reducing surface runoff of hydrophobic pesticides, such as the pyrethroid bifenthrin. The studies analyzed in this report gave a range from 75% to 99% (average 87%) reduction in sediment transport, to which the pyrethroid could potentially be adsorbed to . The actual amount of pesticide reduction via sediment was not available.

Landguard OP-A could be effective in mitigating the effects of chlorpyrifos, diazinon, and malathion on surface water bodies. Study results ranged from 70% to 100% reductions, averaging 85%. Future Landguard products are currently being developed to degrade pyrethroids in runoff. Therefore, the surface water impacts of four of the five representative pesticides could be significantly reduced or eliminated with use of these products. However, commodities employing surface irrigation may see better efficiency than commodities using sprinklers.

6.4.4 Water Treatments: Helpful links and tools

Oregon State offers an extension brochure for PAM (http://extension.oregonstate.edu/catalog/pdf/em/em8958-e.pdf)

6.4.5 Costs

Landguard™: A personal communication with Craig Clarke of Orica Watercare, a publicly-owned Australian company that supplies Landguard, suggest that the total cost of using Landguard would range between $0.50 to $10.00 per acre (Clarke, personal communication, June 17, 2008).

PAM: Integrated Biological Systems, Inc., based in Idaho, quoted a price for granular PAM at around $3 per pound or less, and PAM liquid around $20 to $25 per pint. Granular formulations are the most likely to be used in California agriculture, with liquid mainly employed in areas of steep slope and high erosion problems. 2009 prices and suggested rates are listed in **Table 6-11**, thoughprices were not adjusted using the inflation adjustor, as cost estimates in earlier years are roughly similar.

Nishihara and Shock (2001) recommend an application rate of one pound per acre for the initial irrigation and irrigations following cultivations, with all other irrigations effective at a half pound rate. If there were a total of 14 irrigations throughout the year, with three of the fourteen following cultivations, then the total cost for the season would be a max of $27 per acre (9 lbs at ≤$3 per acre) for material costs, and around $14 per acre for labor application costs (assuming $1 per acre labor cost (Nishihara and Shock 2001)), for a total cost of around $41 per acre.

In summary for BMP comparative purposes, a 50 acre farm would have increased costs averaging $5 per acre or $41 per acre with use of Landguard™ or PAM, respectively, compared to a farm without use. All other production costs are held constant.

Table 6-11. Cost of PAM.
Prices and rates quoted from Integrated Biological Systems, Inc., http://www.intbiosysinc.com/ personal communication 5/4/2009

		Furrow Irrigation		Broadcast	
	Price	**Rate (amt/acre)**	**Cost ($/acre)**	**Rate (amt/acre)**	**Cost ($/acre)**
PAM granular	≤$3/lb	1 (lb)	≤$3	25-35 (lb)	≤$75-105
PAM liquid	$20-25/pint	1 (pint)	$20-25	4-6 (pint)	$80-150

6.5 Conservation Tillage

6.5.1 Definition/Background

Conservation tillage can be defined as minimal or no use of tillage in crop production, and it is often used to reduce soil erosion. Many conservation tillage practices leave a percentage of the soil covered with crop residue after harvest. The next crop can then be planted directly into the stubble, using the residue as mulch.

There are various types of conservation tillage systems: chisel plow, disk and field cultivation, stubble mulch, ridge-till, no-till, and fall strip-till, for which various pros and cons are described in **Table 6-12**. Among these systems, the ridge-till and no-till system are most commonly used as conservation tillage (**Figure 6-6**). In a ridge-till system, crops are planted in the ridges formed during cultivation of the previous crop. Ridge cleaning devices push residue and surface weed seeds off the ridge either during planting or during a separate, pre-planting operation. In a no-till system, tillage is essentially eliminated all together.

Figure 6-6 Ridge-till planted cotton into no-till planted corn residue.
Photo: Jeff Mitchell, UCCE.

Conservation tillage is associated with multiple benefits such as increasing infiltration, reducing runoff and sediment volume, improving soil structure, tilth and productivity, and sequestering carbon.

Table 6-12. Tillage practices: advantages and disadvantages.

System	Typical operations	Major advantages	Major disadvantages
Moldboard plow	Fall or spring plow; 1-2 spring diskings or field cultivations; plant; cultivate.	Suited for poorly drained soils. Excellent incorporation. Well-tilled seedbed.	Major soil erosion. High soil moisture loss. Timeliness considerations. Highest fuel and labor costs.
Chisel plow	Fall chisel; 1-2 spring diskings or field cultivations; plant; cultivate.	Less erosion than from cleanly tilled systems and less wind erosion than fall plow or fall disk because of rough surface. Well adapted to poorly drained soils. Good to excellent incorporation.	Little erosion control. High soil moisture loss. Medium to high labor and fuel requirements.
Disk	Fall or spring disk; spring disk and/or field cultivate; plant; cultivate.	Less erosion than from cleanly tilled systems. Well adapted for lighter to medium textured, well-drained soils. Good to excellent incorporation.	Little erosion control. High soil moisture loss.
Ridge-till	Chop stalks (on furrow irrigation); plant on ridges; cultivate for weed control and to rebuild ridges.	Excellent erosion control if on contour. Well adapted to wide range of soils. Excellent for furrow irrigation. Ridges warm up and dry out quickly. Low fuel and labor costs.	No incorporation. Narrow row soybeans and small grains not well suited. No forage crops. Machinery modifications required.
Strip-till	Fall strip-till; spray; plant on cleared strips; post-emergent spray as needed.	Clears residue from row area to allow pre-plant soil warming and drying. Injection of nutrients directly into row area. Well suited for poorly drained soils.	Cost of pre-plant operation. Strips may dry too much, crust, or erode without residue. Not suited for drilled crops. Potential for nitrogen fertilizer losses.
No-till	Spray; plant into undisturbed surface; post-emergent spray as needed.	Maximum erosion control. Soil moisture conservation. Minimum fuel and labor costs.	No incorporation. Increased herbicide dependence. Some limitations with poorly drained soils, especially with heavy residue. Slow soil warming.

- ## Effectiveness as a BMP

- ## Mitigative

Various studies have shown that conservation tillage systems are effective in reducing pesticide and sediment runoff. The improved soil structure combined with residues left as a type of mulch has been shown to significantly reduce runoff and erosion, thus lowering offsite movement of pesticides dissolved in runoff or attached to sediment (Fawcett et al. 1994, Locke and Bryson 1997, Holland 2004). The results of Mickelson et al. (2001) were more variable, however, concluding that the offsite movement of pesticides under conservation tillage practices was largely dependent on the magnitude of storm events.

Mostaghimi et al. (1987) found that atrazine runoff was reduced by 98% under a conservation tillage system, compared to conventional practices. Clausen et al. (1996) concluded that a conservation tillage system could reduce atrazine and cyanazine runoff by 95% and 77%, respectively.

In addition, numerous studies have documented conservation tillage practices as responsible for cropland agriculture currently acting as a sink for CO_2, rather than a source, as it had historically under higher conventional tillage (Allmaras et al. 2000, West and Post 2002, Lal 2004). Thus, conservation and no-till practices can assist in mitigating the effects of climate change.

However, there are potential tradeoffs associated with conservation tillage as a BMP. Tillage practices such as disking have long been advocated as an alternative practice to manage weeds, and in certain cases, soil dwelling pests (see removal of habitat section). Thus, replacing disking with a conservation or no-till system may actually result in an increased need for pesticide applications, particularly herbicides (Shipitalo and Owens 2006). Any increase in pesticide applications has the potential to increase pesticide inputs to surface waters.

Finally, it is important to consider the effect of conservation tillage on groundwater leaching. While conservation tillage can increase organic matter, and thus increase the potential for pesticide adsorption, it also improves soil infiltration, which can result in pesticide leaching (Seelig 1996). It is therefore possible that conservation tillage may exchange surface water quality impacts for groundwater quality impacts.

In summary, for conservation tillage to effectively mitigate the environmental impacts of pesticides, its ability to reduce overall pesticide runoff and sequester carbon must outweigh any heightened runoff or leaching due to increases in overall pesticide use. The outcome is likely to be highly dependent on the site-specific environmental and management characteristics of each farm.

6.5.2 Representative pesticides and commodities

Of the seven representative commodities, alfalfa, cotton, lettuce, and tomatoes are the most likely candidates for conservation tillage practices as described in this report, often in conjunction with a crop rotation (Bloodworth 1996, Kuepper 2001, Hall et al. 2004). For example, the photograph presented in **Figure 6-6** illustrates ridge-till cotton planted into residue from no-till planted corn. Perennial orchards and vines can practice conservation or no-till as well, although these must include a cover crop in order to have a residue to function as mulch.

If the growers of these commodities were to implement conservation or no-till programs, there is a chance of increased use of herbicides, such as diuron. If the conservation practices reduce runoff and sediment volume, the surface water impact of all representative pesticides may be reduced, and carbon sequestration may be increased. The studies analyzed in this report (Clausen et al. 1996, Mostaghimi et al. 1987) convey a range of reduction in runoff from 77% to 98%, averaging at 88%. However, there could be increased leaching to groundwater, which is of highest concern for diuron and diazinon.

6.5.3 Helpful links and tools

ATTRA – National Sustainable Agriculture Information Service publication on conservation tillage, definitions (http://attra.ncat.org/attra-pub/PDF/consertill.pdf)

The University of California ANR and UCCE hosts a conservation tillage workgroup which sponsors field days (http://groups.ucanr.org/ucct/)

University of Missouri Extension website: No-Tillage and Conservation Tillage: Economic Considerations (http://extension.missouri.edu/publications/DisplayPub.aspx?P=G355)

See federal cost share programs and other financial incentives in the buffer section.

6.5.4 Costs

The financial effects of conservation tillage are variable, with potential for either cost increases or decreases. Cost savings from a no-till or reduced till system can come from lower fuel and machinery costs. However, these savings may be offset if more herbicides are required to control weeds. Conservation tillage may also affect the amount of fertilizer and irrigation water required, as well as yields. Examples of comparisons for various crops using conventional or conservation tillage are listed in **Table 6-13**, where differences in costs and revenue take into account the entire production system and resulting yields. Cost differences ranged from savings of $3,462 per acre, to increased costs of $80 per acre, depending on the cropping system.

For BMP comparative purposes, cropping systems with conservation tillage had an average cost savings of $521 per acre. However, revenues were also generally lower, by an average of $64 per acre. Furthermore, these cost estimates are at a production system level, and therefore include all potential changes in cost that could be affected by implementing conservation tillage, such as changes in herbicide use. Therefore, in contrast to the cost data for previous BMPs, other production costs are not held constant.

Table 6-13. Conservation tillage versus conventional tillage: comparing costs and net returns.
Difference = conservation minus conventional cost, or net return. Costs include all variable and fixed costs for the entire production system from planting through harvest.

Crop System	Cost/acre Difference	Net Returns/acre Difference
Lettuce plus added organic matter (1st trial)[a]	80	305
Lettuce (1st trial) [a]	-410	-70
Lettuce plus added organic matter (2nd trial)[a]	-649	-1
Lettuce (2nd trial)[a]	-649	-1
Lettuce, cover crop, plus added organic matter [a]	-1094	258
Lettuce plus cover crop [a]	-443	291
Broccoli, cover crop, plus added organic matter [a]	-3462	-2076
Broccoli plus cover crop [a]	-702	390
Irrigated soybean[b]	29	-54
Irrigated grain sorghum[b]	5	-28
Irrigated soybean followed by irrigated grain sorghum[b]	15	-19
Irrigated soybean followed by irrigated corn[b]	21	-24
Irrigated cotton[b]	-70	193
Non irrigated soybean[b]	32	-67
Average	**-521**	**-64**

[a] (Jackson et al. 2003), [b] (Parsch et al. 2001)
Values adjusted for inflation to reflect probable 2007 amounts (http://www.westegg.com/inflation/), and converted from per hectare to per acre measures.

7 Pesticide Application

7.1 Definition/Background

Pesticide application methods, including handling procedures, application timing considerations, and choice of equipment, can be effective mitigative BMPs. Attention to the steps listed below can greatly reduce many negative environmental impacts associated with applying pesticides.

7.1.1 Handling Procedures

The site for mixing and loading pesticides must be considered. Central Valley Regional Water Quality Control Board has a draft report on agricultural practices that recommends that the mixing and loading of pesticides take place more than 50 feet away from any wells, streams, canals, irrigation ditches, riparian areas or sinkholes, and more than 200 feet away from any potable water supply wells, to reduce chances of surface water or groundwater contamination (Reyes et al. 2002).

If possible, a containment pad should be constructed with a concrete slab that drains to a central sump. If mixing and loading cannot be done on a containment pad, a site that can be tilled is a better option than hard-packed or paved roadways, where runoff is likely. Sites should be routinely alternated to prevent concentrating pollutants (Reyes et al. 2002)

7.1.2 Equipment loading

Before loading the tank, all hoses and equipment should be checked for cracks and leaks in seals, and the drain plug should be securely in place. Care should be taken to prevent overflow. All drainage should go to sumps rather than sewers or open drainage systems. Protective gear and procedures listed on labels and material safety data sheets (MSDS) should be followed to prevent unnecessary exposure.

7.1.3 Spills

There should be a contingency plan in place in case a spill does happen, with easy access to directions on labels and MSDS sheets where procedures are listed. If a spill occurs or a tank overflows, it should be immediately contained by damming, especially if flowing toward a water body. Cleanup materials such as clay-based kitty litter should always be readily available for emergencies, and disposed of according to label directions. Contaminated soil should be removed immediately, including the removal of a buffer of soil 2 inches deeper than the dampened portions. The soil can be applied to a field if the application rate does not exceed label recommendations (CURES 2000).

“Closed” mixing and loading systems can be developed, such as the one illustrated in **Figure 7-1,** which greatly reduce the likelihood of spills. Use of drylock connectors or other forms of direct connection can pump the pesticide directly from a bulk container to the spray tank, with limited or no handling of the pesticide (Hirschi et al. 1997)

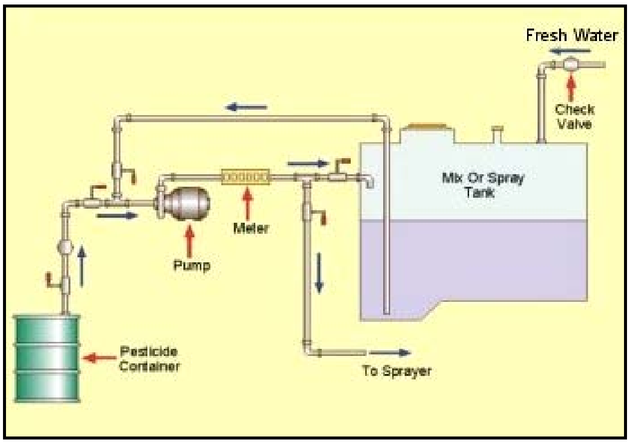


Figure 7-1 Closed pesticide handling system.
Diagram: Ontario Ministry of Agriculture.

7.1.4 Application Timing Considerations

The timing of a pesticide application can play an important role in reducing impact to a number of different environmental components.

- **Rainfall and irrigation**

Many studies have suggested that precipitation and irrigation are very important factors influencing surface water contamination through runoff (Kuivila and Foe 1995, Domagalski et al. 1997, Chu and Marino 2004, Bacey et al. 2005, Zhang et al. 2005, Luo et al. 2008, Zhang et al. 2008a).

Therefore, timing pesticide applications so that they are not immediately followed by a precipitation or irrigation event can assist in preventing runoff and/or leaching. However, the time interval necessary between the application and the water event is subject to the persistence of the pesticide, and may not be feasible for certain pesticides with long residue half-lives.

- **Atmospheric conditions: Wind, humidity, temperature**

The potential for offsite movement of pesticides through drift is affected by meteorological conditions at the time of application, such as wind speed and direction, the relative humidity, and the temperature. Wind speed is probably the most important consideration, since the distance small droplets will be carried increases with the speed of the wind. Hofman and Solseng (2001) recommend a very general guideline of trying to plan sprays when wind speeds are between 2 and 10 miles per hour.

Wind speeds of less than 2 miles per hour can result in temperature inversion conditions, where the air is very calm with little mixing. The atmospheric stability can result in air temperature being cool at ground level, warming as elevation increases, and then cooling again. These inversions often occur in mornings following cloud-free, windless nights.

Under these conditions, it is very easy for small spray droplets to remain suspended mid-air, and move offsite down wind.

In summary, excessively calm or windy conditions are unfavorable for spraying, as they increase the potential for drift of fine droplets. Offsite movement can be largely reduced by avoiding very small droplet sizes as much as possible (Hofman and Solseng 2001). Finally, precipitation or irrigation events following applications can increase volatilization.

7.1.5 Equipment choice and calibration

- Sprayers

As a mitigative BMP, sprayer choice can potentially reduce pesticide drift through use of certain types of technology such as those with cross flow designs or air assist sprayers (e.g. Air Curtain or Air Assist Boom).

As a preventive BMP, the use of a smart sprayer can reduce the amount of pesticide needed, as it is able to selectively target weeds or canopies, thus eliminating wasted spray on bare ground or into the air. Smart sprayers have been developed for both row crops and orchards.

- Nozzles and droplet size

Spray nozzles manage the application rate, droplet size and spray pattern of a pesticide, therefore contributing greatly to both the effectiveness and the safety of the application. Studies by the Spray Drift Task Force (SDTF 1997 a, b) identified droplet size as a highly important factor in influencing whether pesticide moves offsite as drift. Large droplets tend to drop downward, while lighter, smaller droplets are more subject to offsite aerial drift. However, large droplet size is thought to result in less effective foliage coverage, thus potentially requiring higher dosages.

Hofman and Solseng (2001) found that droplets smaller than 100 microns evaporate rapidly and become very small aerosols, which remain in the atmosphere until they fall out with rain. They concluded that drift potential is largely reduced if droplets have a diameter of 150 microns or greater. However foliage coverage is reduced around ten fold due to the increased size. For most herbicides, large droplet sizes are thought to be just as effective as smaller ones. However, smaller droplet size is required by most insecticides and fungicides to achieve desired efficacy (Hofman and Solseng 2001).

Drift can be minimized through lowering the spray nozzle height, using the lower end of the pressure range, and/or increasing the nozzle size for larger droplets. There are also a number of ‘low drift’ nozzles currently on the market, such as Drift Guard (Spraying Systems Co.), air-induction/Venturi nozzles such as the TurboDrop Nozzle (Greenleaf Technologies, Covington, LA), pre-orifice, turbulence chamber nozzles such as the Turbo TeeJet Nozzle (Spraying Systems Co.) or the Turbo Flood Nozzle (Spraying Systems Co.), among others (Hofman and Solseng 2001).

- Shields

Solid or perforated shields can be installed on spray booms or on individual nozzles to reduce drift.

7.1.6 Equipment Maintenance

Before applying a pesticide, applicators should review and follow operating instructions and equipment maintenance recommendations. CURES (2000) recommends the following procedures before each application: rinsing and flushing the spray tank, pumping system and pressure manifolds with clean water to remove debris; inspecting and cleaning all filter screens; lubricating all bearings, grease fittings, and other moving parts; and checking for leaks, cracks or other damage in all hoses and manifolds. If wettable powders are used, nozzles should be inspected frequently and replaced as necessary, as the powder is abrasive and can accelerate nozzle wear. Finally, pressure gauges and regulators should be checked to ascertain that they are in proper working order.

7.2 Effectiveness as a BMP

7.2.1 Mitigative BMPs

- Handling procedures

Keifer (2000) conducted an extensive literature analysis on the effectiveness of handling procedures in reducing impact, including use of personal protective equipment and use of closed pesticide mixing systems. He concluded that while many controlled studies showed effective protection, many real world studies revealed problems, such as protective clothing that was too uncomfortable during the hot months when pesticides were being applied, or the contamination of pesticides through supposedly impermeable materials when subjected to saturation by sprayed vegetation in the field. Overall, the paper concluded that there are not enough real world studies with conclusive measures to evaluate the effectiveness of many of the handling procedures currently available for reducing negative impacts in the field.

- ## Application Timing

To the authors' knowledge, few studies have documented the efficacy of the BMP timing procedures outlined in this report. The Dormant Spray Water Quality Initiative was enacted in 2006 to attempt to mitigate surface water impacts through restricting applications of certain pesticides during the dormant season, when precipitation in California is high (CDPR 2006c). However, monitoring data is currently being analyzed to evaluate the efficacy of this program, thus results are not yet available (CDPR 2009b).

It seems likely that if pesticide applications can be timed so that they do not coincide with events that could cause environmental impact, their impact can be sufficiently reduced. However, given that pest management schedules must meet the timing needs of the crop, application timing as a BMP will not be a viable option in all cases. Scheduling becomes further complicated given the variation in degradation times of different pesticides and persistence of residues. Pesticides that persist in the environment for a long period of time at a toxicity level sufficient to kill pests are likely to be effective pest control options, but are more environmentally problematic, as persistence the probability of environmental exposure. One striking example of the importance of application timing considerations in the use of diazinon is discussed in Section 7.3 This report therefore concludes that conscientious attention to application timing as a BMP, while not likely to increase environmental impact relative to current practices, could range anywhere from a decrease of 0% to 100%, depending on the properties of the pesticide and the unique environmental, meteorological, and management characteristics and events of a given farm.

- ## Equipment choice and calibration

Sprayers, nozzles, and droplet size. Fox et al. (1993) found that a cross flow sprayer with a top fan at a 20^{o} angle reduced downwind drift to about half that of a conventional sprayer. In contrast, Steinke et al. (1992) found that an air curtain sprayer increased downwind drift compared to that of a conventional airblast sprayer. Matthews and Thomas (2000) tested a new nozzle design which directed a fan-shaped air jet at a shallow angle, so that the spray sheet was targeted more toward the crop, thus reducing chances of drift while preserving the finer droplet size for better foliage coverage. Hofman and Solseng (2001) found that air assisted boom sprayers had lower drift when there was a crop canopy, but higher drift if the application was to small plants or bare ground.

Hofman and Solseng (2001) offered the following table comparing the sizes and percentages of small droplets produced by different types of low pressure nozzles (**Table 7-1**):

Table 7-1. Comparing droplet size of different low-pressure nozzles. (Hofman and Solseng 2001)

Nozzles[a] that operate at low pressure		Drop Size (in microns) at different spray volumes and pressures Volume Median Diameter (VMD)			% spray volume < 200 microns
		40 psi 0.2gpm	40 psi 0.5gpm	60 psi 0.5gpm	40 psi 0.5gpm
Extended Range Nozzles					
	XR flat-fan 80°	270	370	300	11
	XR flat-fan 110°	224	310	250	22
Pre-orifice nozzles					
	Drift Guard flat fan 80°	340	410	330	8
	Drift Guard flat-fan 110°	330	390	320	11
Pre-orifice turbulence chamber					
	Turbo flat-fan	340	450	400	6
	Turbo flood flat-fan		710	650	<1
Other Nozzles					
	Flat-fan 80°	270	370	300	11
	Flood flat-fan		450	410	3

[a]All nozzles are Spraying Systems; gpm = gallons per minute; psi = pounds per square inch (Data provided by Spraying Systems Company, 1996)

Gil and Sinfort (2005) conducted a bibliographic review of pesticide emissions during sprayer applications, noting that many studies measure only droplet transport distances to adjacent grounds, but not the transport of the core pesticide that is assumed to remain in the air after water from the droplet evaporates. Without this measurement, air contamination could be underestimated. However, a number of studies reviewed by Gil and Sinfort (2005) point out that the inclusion of non-volatile materials and/or adjuvants in the pesticide mixture can have a significant effect on the evaporative process, and thus the airborne time frame of a droplet. In addition, meteorological conditions will play a large role in the fate of the droplet.

Shields: Shielded sprayers have become increasingly popular and can substantially reduce drift when used with low drift nozzles. Hofman and Solseng (2001) reports that many studies have shown reductions in drift by at least half when a full shield is used, when compared to an equivalent unshielded spray boom, nozzle and pressure. Similar effectiveness is seen using individual nozzle shields.

7.2.2 Preventive BMPs

- **Sensor Sprayers**

Sui et al. (2008) conducted a mini-review of literature pertaining to ground-based sensing systems for weed management. By comparing multiple studies on sprayers guided by computer analysis of images, they found that most smart systems reduced herbicide use by around half of what would be used by a conventional sprayer. Similarly, the California Department of Pesticide Regulation reports that sensor sprayers can reduce pesticide use by 25-40% (Giles and Downey 2005, CDPR 2006b).

7.3 Representative Pesticides and Commodities

Pesticide handling BMPs can prevent surface water quality impacts from spills, particularly for chlorpyrifos, diazinon, and malathion, which are relatively water soluble and are, therefore, relatively mobile in surface water. Application timing BMPs can also greatly reduce impacts to surface water quality by reducing the amounts of dissolved and sediment-bound pesticides that runoff during storm or irrigation events. Application timing is especially important for diazinon. A supplemental label for dormant applications of diazinon contains the following timing restrictions (there are additional restrictions not specific to timing):

1. "Do not apply this product to orchards when soil moisture is at field capacity and/or when a storm event likely to produce runoff from the treated orchard is forecasted by NOAA/NWS (National Weather Service) to occur within 48 hours following application."

2. "Apply only when wind speed is 3-10 mph at the application site as measured by an anemometer outside of the orchard on the side nearest and upwind from a sensitive site."

3. "When sensitive aquatic sites are downwind from orchards, spray the first three rows nearest the sensitive aquatic sites only when the wind is blowing away from the sites. The row at the edge of the field next to sensitive aquatic sites must be sprayed with the outside nozzles turned off. Spray must not be directed higher than the tree canopy, and spray must be directed away from sensitive aquatic sites."

Longer periods of time between pesticide applications and storm events or irrigation events allows for more degradation of the pesticide, so there is less of it to be moved off-site in runoff.

7.3.1 Helpful links and tools

The Coalition for Urban/Rural Environmental Stewardship (CURES) manual for safe mixing and loading

English:(http://www.curesworks.org/publications/mixload.pdf) Spanish: (http://www.curesworks.org/publications/mixloadSpanish.pdf)

The University of Illinois offers guidelines for mixing and loading: (http://www.thisland.uiuc.edu/60ways/60ways_55.html)

Application Timing:

Pesticide Regulation's Endangered Species Custom Realtime Internet Bulletin Engine (Prescribe) online database (http://www.cdpr.ca.gov/docs/endspec/prescint.htm)

Equipment:

NRCS cost share assistance for sensor sprayers (ftp://ftp-fc.sc.egov.usda.gov/CA/programs/EQIP/2008/2008_Precision_Pest_Control_Fact_Sheet.pdf)

7.3.2 Costs

Of the BMPs listed under pesticide applications, handling procedures and timing considerations are very difficult to gauge economically. A change in handling procedures could result in a cost increase or decrease, depending on the current procedures being replaced, as well as any reduction in exposure health costs that could occur as a result.

Changes in the timing of an application may not result in any cost changes, if the application is simply delayed to a more appropriate time. However, if the application is replaced by a lower risk pesticide or another form of pest control, cost may increase or decrease. If the delay in application or the substitution of a different practice results in increased pest pressure, a higher amount of pesticide could be needed later, resulting in increased costs, or yields could decline, resulting in decreased revenues.

Equipment-based BMPs are likely to have the strongest financial impacts. Swinton et al. (1997) analyzed differences in net present cost per acre of a standard conventional air blast sprayer, an airblast sprayer with a tower boom, an airblast sprayer with both a tower boom and SmartSpray^{TM}

technology, and an Air Curtain Curtec™ C2000 sprayer. Initial costs were generally higher for lower risk sprayers as compared to the conventional airblast sprayer. As shown in **Table 7-2**, costs for the drift reducing tower boom and Air curtain sprayers, increased from $6,436 to $24,259, while costs for the pesticide-use-reducing sensor sprayer increased by $33,470.

However, when these costs were balanced against savings in pesticide use over time, the lower risk sprayers were more economical over a 10 year period. For a 50 acre farm, the Air Curtain sprayer proved the most economical at $504 per acre, followed by the Airblast sprayer with tower boom at $523 per acre, the sensor sprayer at $545 per acre, and finally the conventional standard airblast sprayer at $562 per acre. Results were highly dependent on the size of the farm, with the sensor sprayer being more economical than the airblast with towerboom when the farm was around 200 acres **(Table 7-3).**

A recent article in the Western Farm Press advocated orchard smart sprayers as cost savers. It concluded that the cost of a multiple-eye smart sprayer could be recovered within two years for a 300 acre almond orchard, largely due to reductions in pesticide costs, sprayer fuel and labor. In addition, it reported that the 2008 Environmental Quality Incentives Program (EQIP) has cost share money for growers in the San Joaquin valley, paying around $30 per acre for up to a maximum of 500 acres (Niederholzer 2009). With EQIP financial incentives, sensor spray technology is the most economical of the five sprayers analyzed in **Table 7-3**. The Department of Pesticide Regulation estimates that a smart sprayer costs around $30,000 (CDPR 2006a).

In summary, for BMP comparative purposes, costs for pesticide handling and application timing could not be accurately estimated. However, the costs of using a sprayer that reduces drift (Airblast with tower boom and Air Curtain) analyzed in this report ranged from $6,436 to $24,259 more than a conventional air blast sprayer, with maintenance costs $0 to $643 per year more. Given the range of estimated cost for different types of sensor sprayers (DPR: $30,000 to Swinton et al. (1997): $105,551), a switch from a conventional sprayer to one with SmartSpray technology could result in anywhere from a cost savings of $42,091 to a cost increase of $33,470.

While these estimates were based on a 200 acre farm, they are unlikely to significantly differ for the 50 acre farm we are using as a framework for comparisons. Therefore, dividing these totals by 50 acres gives a range of initial year cost per acre for low drift sprayers of $129 to $489 per acre (average $309 per acre) and a maintenance cost range from $0 to $13 per acre (average $6 per acre). For sensor sprayers, costs would range from a savings of $842 per acre to an increase of $669 per acre, averaging at a savings of $86 per acre. These estimates should be viewed as the out of pocket cost changes that might occur if a grower was to switch from a conventional airblast sprayer to a drift reducing or sensor sprayer.

In addition to these basic costs, a net present cost analysis annualized over 10 years was done for these sprayers. This cost comparison incorporates both initial and maintenance costs, as well as potential cost offsets such as savings over time due to reductions in pesticide use. If these factors are included, use of a low drift sprayer would result in an average cost savings of $49 per acre, with a range from $39 to $58 per acre. Use of a sensor sprayer would result in an average cost savings of $32 per acre, ranging from $17 to $47 per acre in savings.

Table 7-2. Cost estimates for sprayers: initial and annual maintenance (Swinton et al. 1997).

Sprayer	Initial cost	Annual Maintenance
Conventional Airblast Sprayer	$74,830	$668
Airblast Sprayer with tower boom	$81,511	$668
Airblast Sprayer with tower boom and **SmartSpray™** technology	$109,572	$668
Air Curtain Sprayer	$100,219	$1,336

Prices adjusted for inflation to reflect probable 2008 prices (http://www.westegg.com/inflation/)

Table 7-3. Net present cost comparison of different types of sprayers. Analysis for Michigan apple production, annualized over 10 years - combining installation and maintenance costs (Swinton et al. 1997).

Sprayer	Net present Cost per acre 50 acre farm	Net present Cost per acre 200 acre farm
Conventional Airblast Sprayer	$562	$392
Airblast Sprayer with tower boom	$523	$347
Airblast Sprayer with tower boom and SmartSpray™ technology	$545 ($515 w/EQIP)	$315 ($285 w/EQIP)
Air Curtain Sprayer	$504	$289

8 Preventive Best Management Practices

Determining the effectiveness of preventive BMPs in reducing environmental impact from pesticides is a complex task, where conclusions are always conditional on a multitude of factors spanning both agricultural practices and environmental, ecological, and commodity-specific characteristics. If a pesticide causing environmental impact can be replaced by a preventive practice, then that practice is a very effective BMP, completely eliminating the risk attached to use of that pesticide. However, very few of the many studies on different preventive BMPs have measured their effectiveness in these terms, with most reporting changes in pest abundance, mortality, or activity instead. For the grower, however, percentage changes in these variables, no matter how large or significant, are unlikely to translate into efficacy unless they enable a decrease in pest populations or commodity damage below the grower's economic threshold level. Only then might the grower be able to successfully replace a pesticide with the preventive BMP, and thus eliminate the environmental impact associated with the pesticide. Because preventive BMPs are poor or nonexistent for many pest species, only certain pests can be controlled using current preventive BMPs, while the grower must employ other forms of pest control for the remaining pests.

8.1 Biological Control

8.1.1 Definition/Background

Effective biological control can be defined as the suppression of a pest species below economically damaging levels by natural enemies. Suppression can occur via direct methods such as mortality of the pest, or through indirect methods such as a reduction in the pest's reproductive capabilities or inhibition of commodity-damaging activities. When effective, biological control can significantly reduce or eliminate the need for pesticides to control these particular pests, thus lowering potential pesticide risks to people and the environment. It is therefore included as a preventive BMP.

Natural enemies include *predators* which attack and kill pests (**Figure 8-1**), *parasites* which spend most of their life attached to or within a host (**Figure 8-2**), ultimately weakening or killing the pest, *herbivores* which can help to suppress weeds, *competitors* which can out-compete pests for valuable resources but are not pests themselves, or species which inhibit pest activities through *antibiosis or alleleopathy*, the secretion of chemical substances that inhibit pest activity or create toxic environments that limit growth. Of these natural enemy types, predators and parasites have been the most studied in the context of biological control use in agriculture (Flint and Dreistadt 1998). *Pests* that can be controlled biologically include insects, mites, nematodes, plant pathogens, and weeds, among others. Biological control has been most effective for arthropod (insects and mites) pests, with less success seen on nematode, plant pathogen, and weed pests (Flint and Dreistadt 1998).

Figure 8-1 Biological control: predator-prey.
Multicolored Asian lady beetle eating winged soybean aphid.
Photo: Marlin E Rice

Figure 8-2 Biological control: aphid parasite.
Copyright: Peter J. Bryant (pjbryant@uci.edu). This parasitic wasp (Aphidius testaceipes) deposits eggs into aphids, leading to the death of the aphids.
Photo: http://nathistoc.bio.uci.edu/hymenopt/Aphidius.htm

- Three classes: naturally occurring/conservation, augmentative, and classical.

Naturally occurring biological control is widespread in nature, with natural enemies adequately regulating many organisms which could otherwise become potential agricultural pests. Secondary pest outbreaks are thought to occur when some disruption, such as a pesticide application, upsets this relationship and allows the population of the potential pests to grow unchecked. Naturally occurring biological control is often referred to as "conservation biological control" when it is cultivated through environmental manipulation. Environmental manipulation includes limiting and timing the use of pesticides known to harm natural enemies, as well as creating habitat that can assist in establishing natural enemies in the field, such as providing shelter against environmental elements and supplying alternative sources of prey for times when pest pressure is low.

Augmentative control, in contrast, is the intentional release of natural enemies, often laboratory-raised, to supplement those naturally occurring in the field. Besides increasing the population size of natural enemies, augmentative releases can allow timing to insure overlap of the natural enemy with the pest, thus preventing spatial and/or temporal gaps between pest pressure build-up and biological control. Augmentative control also allows for selection of natural enemies that are thought to be better at controlling a given pest than those that are already present in the field.

Classical biological control is the release of imported, non-native enemies in an area where they were not previously established, often in response to an exotic pest species that has become invasive due to lack of natural enemies. Classical control requires extensive precautionary research and quarantines to insure that the introduced natural enemy will not become a pest itself or cause disruption to native ecosystems. Thus it is only carried out by highly trained researchers from government or academic institutions. While many instances of classical biological control have been highly successful, it will not be further addressed in this section as a BMP, due to the limitations of implementation by those outside of scientific institutions.

8.1.2 Effectiveness as a BMP

- Preventive

The efficacy of biological control as a preventive BMP is largely inconclusive, since most studies lack results pertaining to whether pest pressure reductions through biological control were sufficient to replace the need for pesticides. Many studies in this area were conducted by researchers atvarious campuses of the University of California. The complex issues surrounding the probable effectiveness of the different biological control classes are summarized below.

Augmentative Control. Many issues can affect the efficacy of augmentative biological control. The quality of the purchased natural enemies can factor into how many survive or hatch upon release. The amount, distribution, and types of prey available in the field, in addition to sufficient habitat, can affect long term survival and establishment of released organisms as well as prevent unwanted migration from the field. Finally, the composition of species in the field can result in intraguild predation, where the released enemy is predated upon, or apparent competition, where pressure on the pest by the natural enemy is diluted due the presence of alternative prey (Rosenheim et al. 1995, van Veen et al. 2006).

In an evaluation of augmentative biological control by Collier and van Steenwyk (2004), the authors reviewed over 140 biological control studies, finding only 31 that reported whether biological control was effective enough to lower pest abundance or commodity damage to the grower’s threshold level, thus eliminating the need for pesticide use. Of these 31 studies, only 15% concluded that biological control effectively eliminated the need for pesticide. In the same publication, seven of the reviewed studies included comparisons of pest suppression between biological control and pesticides, with the majority concluding that the pesticides had stronger suppression than biological control. That review paper has been criticized, however, as painting an incomplete picture of the effectiveness of biological control, due to the small sample size of studies meeting the reviewers' criteria for inclusion, among other deficiencies (van Lenteren 2006).

Conservation control: Habitat manipulation. There can be spatial and temporal gaps between pest outbreaks and establishment of natural enemy populations large enough to control pest populations, resulting in damage to the commodity. These time lags between the colonization of a field by a pest and the appearance of its natural enemies can be caused by a wide assortment of factors, including distance of migration, variation in dispersal methods, reproduction methods, prey preference/availability within the field and surrounding areas, and meteorological considerations that can effect dispersal mechanisms, among others (Bellows and Fisher 1999, Nicholls and Altieri 2004).

Studies specific to the efficacy of habitat manipulation to promote biological control are difficult to interpret, largely due to a stronger focus on community ecology, rather than the applied ecology aspects of agriculture. Thus, results pertaining to conservation control's effectiveness at replacing the need for pesticides are limited. Gurr et al. (2000) reviewed 51 studies on habitat manipulation for conservation biological control. All the studies reported on changes to the natural enemies, but only 30 reported changes to the pest population, and just eight included changes to the commodity damage. Forty six of the 51 (90%) studies showed that habitat manipulation had a predominantly positive effect on natural enemies, while 21 out of 30 (70%) reported a positive result on pest influence reduction, and four out of eight (50%) reported a beneficial result to the commodity. While the last percentage relating directly to the commodity is the most important to the grower, the small sample size of studies available suggests it may not provide an accurate reflection of biological control efficacy.

Conservation control: Pesticide selection. Besides habitat manipulation, conservation biological control also advocates the use of selective pesticides that are of lower risk to natural enemies. Many broad spectrum pesticides can harm natural enemies through direct contact, elimination of hosts or sources of prey, repellant effects generated by residual activity, and/or sublethal effects, such as impacts on developmental rates, foraging behavior, navigation, and feeding (Ehler and Endicott 1984, Hoy and Dahlsten 1984, Purcell and Granett 1985, Hoy and Cave 1989, Yardim and Edwards 1998, Epstein et al. 2001, Komeza et al. 2001, Zalom et al. 2001, Agnello et al. 2003, Armenta et al. 2003, Prischmann et al. 2005, UC-IPM 2005, Desneux et al. 2006, 2007). In general, natural enemies are thought to be more susceptible to pesticides and to recover at a slower rate than pests. Thus secondary pest outbreaks or resurgences of a primary pest can occur as a result of the pesticide application releasing the pest from natural enemy control (Dutcher 2007). In a study evaluating the role that pesticide choice plays on the effectiveness of biological control in California walnuts, a significant difference in the need for treatment of secondary mite pests was found between growers who used pesticides known to be harmful to natural enemies and those who did not (Steinmann and Zhang submitted).

8.1.3 Effectiveness for reducing pest pressure

In a meta-analysis by Stiling and Cornelissen (2005), the authors reviewed 145 studies representing a mixture of natural, augmentative, and classical biological control, reporting changes in pest abundance (73% decrease), parasitism (301% increase), pest mortality (390% increase), weed biomass (56% decrease), weed flower abundance (63% decrease), and weed seed production (59% decrease) when natural enemies were present (percentages are transformed from the log proportional percentages reported in the original articles). Similarly, a mini-review by Ojiambo and Scherm (2006) found that biological control was "moderately effective on average" for disease suppression, with higher effectiveness seen on annuals than on perennials. Unfortunately, results such as this do not allow inference as to whether the changes in the pest numbers met the economic threshold levels needed by growers to eliminate a pesticide application.

In summary, it appears that the strongest conclusions that should be made from the existing literature is that habitat manipulation, use of selective pesticides, and augmentation can all increase natural enemy populations, and in many instances, reduce pests. However, whether the pest suppression capacity of the natural enemies is sufficient to replace pesticides remains largely inconclusive.

Biological control as mitigative BMP. Besides enabling biological control to act as a preventive BMP, habitat manipulation can potentially serve as a mitigative BMP as well if planted vegetation serves to filter pesticide and sediment runoff as a buffer or block pesticide drift from offsite movement as a windbreak. Please refer to sections on buffers, cover crops, and windbreaks for a more detailed analysis of potential mitigative efficacy.

8.1.4 Representative pesticides and commodities

Biological control had the broadest impact when compared to the other preventive BMPs advocated as potential pest controls by UCIPM. It is listed for 33 different pest-commodity combinations among the representative pesticides and commodities chosen for analysis in this report. Including the minor pests, 28 pest-commodity combinations could potentially replace bifenthrin with biological control, followed by 18 combinations that could replace either chlorpyrifos or malathion, and 14 combinations that could replace diazinon (CDMS 2009, UC-IPM 2009) (**Table 8-1**). Biological control could therefore potentially reduce surface water quality impacts, VOCs, and toxicity to human health and wildlife.

Table 8-1. Number of pests for each commodity which are traditionally controlled by representative pesticides but could potentially be managed by biological control. CDMS 2009, UC-IPM 2009

Commodity	Bifenthrin	Chlorpyrifos	Diazinon	Malathion
Alfalfa	2	4		4
Almond	4	5	1	
Cotton	8	6		5
Grapes		1	4	4
Lettuce	4		2	2
Tomato	5		3	1
Walnut	4	2	4	2
Total	**28**	**18**	**14**	**18**

8.1.5 Helpful links and tools

Numerous websites list relative toxicities of pesticides to different natural enemies (Theiling and Croft 1988, Biobest 1999, Koppert 2005, UC-IPM 2009, USDA 2009). Some representative examples include:

UC IPM online (http://www.ipm.ucdavis.edu/PMG/crops-agriculture.html)

Pest management strategic plans put out by USDA Regional IPM Centers Information Systems (http://www.ipmcenters.org/pmsp/index.cfm)

SELECTV (http://ipmnet.org/phosure/database/selctv/selctv.htm)

Koppert (http://side-effects.koppert.nl/)

Biobest.be (http://207.5.17.151/biobest/en/neven/default.asp)

The following manuals can assist with planning, supplies, and management of habitat to promote biological control (Dufour 2000, Earnshaw 2004):

Farmscaping to Enhance Biological Control, Pest Management Systems Guide (http://attra.ncat.org/new_pubs/attra-pub/PDF/farmscaping.pdf?id=California)

Hedgerows for California Agriculture, A Resource Guide (http://www.caff.org/programs/farmscaping/Hedgerow.pdf)

8.1.6 Costs

Costs of biological control are highly variable, depending on the pest, the commodity, and how implementation is approached. Using the natural enemy rates from the Collier and van Steenwyk (2004) review that were deemed effective at replacing the need for pesticide combined with prices for natural enemies as sold by Ricon-Vitova Insectaries adjusted to 2007, augmentative control averaged $859/acre, with a minimum of $43/acre and a maximum of $1,674/acre (Ricon-Vitova 2006) (**Table 8-2**).

Table 8-2. Costs: replacing pesticides with augmentative biological control. Rates that effectively reduced pests below threshold levels in order to replace the need for pesticide use (Collier and van Steenwyk, 2004).

	Pest	Natural Enemy	Release Rate[a]	Unit[b]	# Units	Price ($)/ unit[b]	Cost ($)/ha	Cost ($)/acre
citrus	Aonidiella	Aphytis	50,000	10,000/ cup	5	22	111	45
apples	Tetranychus	Metaseiulus	85,760	1,000/ bottle	86	12	1,056	427
hops	Tetranychus	Phytoseiulus	22,000	1,000/ bottle	22	13	280	113
corn	Tetranychus	Phytoseiulus	350,000	2,000/ bottle	175	19	3,306	1,338
corn	Tetranychus	Amblysieus	350,000	1,000/ bottle	350	12	4,294	1,738

[a] Rate (number of organisms released per hectare) that was effective at replacing the need for an insecticide Collier and van Steenwyk (2004)
[b] Unit and price from Ricon-Vitova (Ricon-Vitova 2006) Least expensive unit option chosen when multiple units available. Prices adjusted for inflation to reflect probable 2008 prices (http://www.westegg.com/inflation/)

Establishment of an insectary hedgerow generally ranges from $1 to $4 per linear foot (Earnshaw 2004). Using the UCCE budget estimated for a perennial hedgerow on the Central Coast, a 1000 linear foot hedgerow (width 8 ft) would cost around $2,660 ($0.33 per square foot) for installation and $580 ($0.07 per square foot) for annual maintenance (costs adjusted for inflation to reflect 2007). As described in the windbreak section, a hedgerow for a 50 acre farm was estimated to be around $633 per acre and $134 per acre for implementation and maintenance costs, respectively.

If the hedgerow is planted on land that would otherwise be used for production, the commodity revenue can be reduced (See Definitions: Opportunity Costs, and **Table 1-3**). In contrast, the hedgerows can include plants that bring in extra income to offset costs and increase overall revenue, such as pomegranate, mulberry, citrus, pineapple guava, and various herbs (Earnshaw 2004). In addition, if biological control can effectively replace the need for pesticides, overall pest management costs may be reduced. In a study of walnut growers in San Joaquin, Stanislaus, and Merced counties, it was found that if biological control was effective and the grower used solely selective alternative pest control products, the costs of 44% of the pest management strategies analyzed could have been reduced by an average of $52/acre. The remaining 56% saw an increase in costs of $56/acre, however (Steinmann et al. Submitted).

There are also many federal cost share programs that can assist in habitat management for various conservation purposes (see buffer section).

For BMP comparative purposes, costs would increase by an average of $859 per acre to implement augmentative biological control and by an initial cost of $633 per acre with yearly maintenance of $134 per acre to implement a hedgerow as a method to increase habitat availability for natural predators. These estimates assume all other production costs are held constant, which may be an incorrect assumption if the biological control is sufficient to replace or reduce the need for pesticide applications.

8.2 Pesticide Choice

8.2.1 Definition/Background

Pesticide choice includes choices in both the product as well as the formulation choices. There are a number of alternative pest controls that can potentially be substituted for higher risk products. These alternative controls are often more selective in the range of species that they target, thus reducing or eliminating much of the unintended harm to the environment that can occur with broad spectrum controls.

Alternative controls cover a broad range of modes of action, including microbial formulations, pheromone mating disruption, insect growth regulators (IGRs), and botanical products, among others. There is a wide variation in costs as well as in their effectiveness in controlling pests. They are also often associated with a need for greater attention to application timing and monitoring, and can thus have a higher learning curve compared to conventional products with which the typical grower is likely to be more familiar.

In addition to choice of alternative products, the choice of the product's formulation can affect its impact on the environment as well. Common pesticide formulations include emulsifiable concentrates (ECs), granules, solutions, flowables, aerosols, dusts, wettable powders, soluble powders, and baits. The formulation of a pesticide describes its physical state and determines its application method, thus significantly affecting the transport and fate of the pesticide.

For example, emulsifiable concentrates have been found to be the greatest contributors of VOC emissions compared to other formulations. Therefore, substituting dry formulations of a given pesticide for EC formulations may significantly decrease pesticide VOCs (EPA 1993). In addition, certain formulations such as wettable powder bags and microencapsulation can reduce exposure while mixing and loading, thus decreasing potential risks to pesticide applicators.

8.2.2 Effectiveness as a BMP

- Preventive

The substitution of lower risk pest controls and/or formulations for high risk counterparts can substantially lessen or eliminate environmental impacts, and is therefore considered to be an effective preventive BMP. It can be difficult, however, to correctly assess the probable environmental impact of a given pest control. Many alternative controls can be low risk in one environmental aspect, but not in another. Such products are often given the label of 'alternative', and not subjected to the rigorous testing of impact to multiple sources that a higher risk pesticide is likely to undergo. Thus, an alternative product that is safe for humans may not be safe for natural enemies or some other segment of the environment.

In addition, although a wealth of data in the form of toxicity and exposure studies currently exists, it can still be very difficult for growers and other stakeholders to obtain needed knowledge on environmental impacts of a given pest control product. Such information is often contained in disparate sources requiring a vast amount of effort and scientific education to arrive at useful interpretations and conclusions.

8.2.3 Representative pesticides and commodities

Table 8-3 lists a sample of alternative products that could be substituted for the five representative pesticides analyzed in this report, as recommended by UCIPM online for the major pests of the seven representative commodities. This list is not all inclusive, and is not meant as a recommendation or an implication of equivalent pest control efficacy to the representative pesticides. "Alternative" was defined as pest control products listed in either the Organic Materials Review Institute (OMRI) of acceptable materials for certified organic production, the EPA reduced risk/OP alternative list, or the EPA Biopesticide list (EPA 2007a, b, OMRI 2008).

By definition, the choice of an alternative pesticide as a replacement for a representative pesticide reduces use of the representative pesticide by 100%, and therefore prevents it from entering the environment. However, it is important to note that while alternative products are generally lower risk to humans, they are not always lower risk to other aspects of the environment, as can be seen in **Table 8-3**. For example, certain low risk controls have moderate to high risk for beneficial arthropods, bees, air, or aquatic species. Their effectiveness as a BMP in lowering risk is therefore highly variable and dependent on which aspects of the environment are being evaluated. It is thus very important to select the alternative pest control with lowest risk to the components of the environment most likely to be harmed, given the unique spatial and environmental characteristics associated with each farm.

Table 8-3. Estimated impact levels of alternative pest controls. Alternatives considered to be of lower risk to the environment.
L = low concern, M = moderate concern, H = high concern (EXTOXNET 1996, Biobest 1999, Sullivan 2000, CDPR 2003, Koppert 2005, CDPR 2009d, EPA 2009)

Use and Chemical Class	Alternative control	Water/aquatic species	Air	Birds	Beneficial Arthropods/ other
Herbicides:					
Aryl Triazolinone	Carfentrazone	L-M	L	L	Unknown
Phosphonoglycine	Glyphosate	L	H[a]	L	L
Insecticides:					
Diacylhydrazine (IGR)	Methoxyfenozide	M: fish/aquatic invertebrates	M[a]	M	L-M (M: bees)
Pyridine (IGR)	Pyriproxyfen	M-H	L	L	L: bees, H: predators
Microbials	Spinosad	L	L	L	H: bees
	Bacillus Thuringiensis	L	L	L	L
Botanicals	Azadirachtin	L	L	L	L
Miticides:					
Diphenyloxazoline	Etoxazole	H: aquatic invertebrates	L	L	M-H
Carbazate	Bifenazate	H: fish/aquatic invertebrates	L	L-M	M: bees

[a]Glyphosate isopropylamine salt listed in top 10 VOC producing active ingredients for South Eastern desert non-attainment area. Methoxyfenozide is not listed as a top 10 ai, but contributed a similar amount of VOCs as those listed as problematic.

8.2.4 Helpful links and tools

Given that it may be difficult to find effective pesticides that are low risk to all aspects of the environment, an understanding of which environmental components are likely to be affected by each individual pesticide application based on the unique spatial, temporal, topographical, and meteorological conditions of the application site is necessary to minimize risk. The following websites are available or soon to be available, to assist growers and other stakeholders in assessing the probable environmental impact of different pesticides given their unique environmental site characteristics:

UCIPM WaterTox: users can input site/management specific information to compare risks of pesticides for leaching and runoff potential (http://www.ipm.ucdavis.edu/TOX/simplewatertox.html)

Tools soon to be available online:

Pesticide Use Risk Evaluation (PURE) tool and National IPM Options Evaluation Tool: allow users to input their site/management specific information to assess impact to surface water, groundwater, air, beneficial insects, wildlife, and human health.

The following websites can assist growers in assessing the probable efficacy of low risk products at controlling specific pests:

Arthropod Management Tests, Entomological Society of America (must be a member or subscribe to access test results)
(http://www.entsoc.org/pubs/periodicals/amt/index.htm)

Pest Management Strategic Plans, completed by the Western IPM Center, often have efficacy tables in the appendices, assigning ranks to different pesticides based on their effectiveness in controlling a specific pest on a given commodity.
(http://www.ipmcenters.org/pmsp/pmsp_form.cfm?usdaregion=National%20Site)

8.2.5 Costs

The economic viability of alternative pest controls is largely dependent on the material cost of the product, the number of applications, the amount of monitoring needed, any associated learning curve, and the efficacy of the product in controlling the pest. As a result of these factors, many growers perceive alternative controls to be more expensive than their conventional counterparts.

One important aspect that should be considered in the cost calculations, however, is the idea that use of alternative selective products is often less likely to harm natural enemies compared to conventional broad spectrum products (Zalom et al. 2001, Agnello et al. 2003, Prischmann et al. 2005). Consequently, it is possible that any higher costs of alternative pesticides may be offset in part if the selective nature of the alternative product can promote biological control of secondary pests and eliminate the need to control these secondary pests with pesticides, thus saving the grower money.

In contrast, it is also important to consider the possibility that the substitution of broad spectrum high risk pesticides with selective alternative controls may result in the emergence of new pests that were previously controlled by the broad spectrum pesticide. This development could increase the diversity of pests seen in a season, and possibly generate the need for additional pesticides. It is therefore very difficult to estimate how a grower's pest management costs will change upon switching from conventional to alternative products. However, in a study of arthropod pest management strategies used by walnut growers in California, 43% of the strategies were expected to be able to be substituted by alternative low risk products at either the same or less cost to the grower, if naturally occurring biological control of secondary pests could be realized (Steinmann et al. Submitted).

Table 8-4 compares the costs of one application of the representative pesticides with that of the alternative products. Label use rates of each pesticide varied by commodity and pest, and prices varied by amount purchased and distributor. Average rates and prices were therefore used to get an estimate of costs. These costs were then averaged over pesticide types and formulations to facilitate comparisons between the representative pesticides and the alternative products.

The representative insecticides/miticides averaged $33/acre, compared to an average of $42/acre for alternative insecticides and $72/acre for alternative miticides. Although many of the representative insecticides claim to control mites, they are not likely to be used as a primary mite control, as there are many more effective acaricides on the market. Therefore, the comparison of the representative insecticides with the alternative miticides is less informative than with the alternative insecticides, but is still useful in showing the trend of alternative products often being more expensive than their conventional counterparts. This trend was not apparent in the herbicides, however, with the alternative herbicides averaging $11/acre compared to the higher average of the diuron herbicides at $26/acre. Therefore, as an estimate, a grower substituting an alternative product for a representative product could see anywhere from a cost savings of $15 per acre (average herbicide) to a cost increase of $39 per acre (average miticide), with a mean increase of $12 per acre.

The cost of formulations can be seen in **Table 8-5**, where the cost of both a dry and aqueous formulation of each representative pesticide is given. With the exception of chlorpyrifos, the dry formulations, which are generally expected to have lower environmental impacts, were more expensive per application per acre than the aqueous formulations. By changing to a dry formulation, costs could change from a savings of $14 per acre (chlorpyrifos) to an increase of $39 per acre (malathion), with an average increase of $18 per acre.

For BMP comparative purposes, a grower switching from a conventional to an alternative pest control would see an average increase of $12 per acre, while a grower switching from a wet to a dry formulation would be likely to see an average increase of $18 per acre. These estimates hold all other production costs constant, which may not be an accurate assumption since the replacement of broad spectrum pesticides by selective products could increase biological control efficacy, thus reducing the need for pesticides, or it could allow for new pests to emerge, and increase the need for pest control. In addition, the estimates do not account for differences in the numbers of applications needed to treat a pest in over the season.

Table 8-4. Prices of representative and alternative products. Prices: (De Moura 2009). Adjusted for inflation to 2008: http://www.westegg.com/inflation/.

		Active Ingredient	Product	Price	Unit	Average use rate per acre (product)[a]	Cost per acre
Representative Pesticides	Insecticides/ Miticides	Bifenthrin	Brigade Wsb Insecticide/Miticide	47	LB	0.813	38
		Chlorpyrifos	Lorsban 4E Insecticide	60	GA	0.5	30
		Diazinon	Clean Crop Diazinon 50Wp	9	LB	5	46
		Diazinon	Diazinon Ag 500	44	GA	0.25	10
		Malathion	Gowan Malathion 8	52	GA	0.875	46
	Avg. rep. insecticides/miticides						34
	Herbicides	Diuron	Karmex Df Herbicide	6	LB	5.5	33
		Diuron	Diuron 4L	26	GA	0.75	20
	Avg. rep. Herbicides						26.5
Alternative Pesticides	Insecticides	Methoxyfenozide	Intrepid 2F	320	GA	0.055	18
		Pyriproxyfen	Esteem 0.86 Ec IGR	873	GA	0.117	102
		Spinosad	Success	896	GA	0.047	43
		Spinosad	Entrust	539	LB	0.109	59
		Bacillus Thuringiensis	Deliver Biological Insecticide	22	LB	1	22
		Bacillus Thuringiensis	Dipel Es	47	GA	0.438	21
		Azadirachtin	Aza-Direct	230	GA	0.188	44
	Avg. alt. insecticides						44.1
	Miticides	Etoxazole	Zeal	514	LB	0.125	64
		Bifenazate	Acramite 50Ws	86	LB	1	86
	Avg. alt. miticides						75
	Herbicides	Carfentrazone	Shark Herbicide	1048	GA	0.008	8
		Glyphosate	Roundup Original Max	61	GA	0.234	15
	Avg. alt. herbicides						11.5

[a] Estimated use rate of product for one application based on average use rates listed on pesticide labels for all crops and pests

Table 8-5. Prices for different formulations of representative products.
Prices: De Moura, 2009. Adjusted for inflation to 2008:http://www.westegg.com/inflation/

Active Ingredient	Formulation	Product	Price ($)	Unit	avg rate/acre	Cost ($)/acre
Bifenthrin	Dry	Brigade Wsb Insecticide/Miticide	47	LB	0.813	38
Bifenthrin	Aqueous	Capture 2EC	613	GA	0.03	19
Chlorpyrifos	Dry	Lorsban 15G	2	LB	6.6	16
Chlorpyrifos	Aqueous	Lorsban 4E Insecticide	60	GA	0.5	30
Diazinon	Dry	Diazinon 50 WP	9	LB	5	46
Diazinon	Aqueous	Diazinon Ag 500	44	GA	0.25	10
Malathion	Dry	Malathion 5 Dust	1	LB	77.5	91
Malathion	Aqueous	Malathion 8EC	58	GA	0.875	51
Diuron	Dry	Karmex Df Herbicide	6	LB	5.5	33
Diuron	Aqueous	Diuron 4L	26	GA	0.75	20

[a] Estimated use rate of product for one application based on average use rates listed on pesticide labels for all crops and pests

8.3 Removal of Pest Habitat and Resources

8.3.1 Definition/Background

The removal of pest habitat and resources can strongly limit the pest's impact on a commodity. There are a number of ways to achieve this, such as disking the soil, cultural weed management practices, crop rotation, removal of plant debris and other forms of habitat, and the timing of the harvest and/or planting of the crop. In particular, disking and weed management can also potentially destroy the pest itself, thus improving their efficacy as a cultural pest control beyond just pest habitat destruction.

Disking: For pests that spend some portion of their life cycle in the soil, the disking of the field can greatly reduce their population numbers through the destruction of habitat, increased exposure to natural enemies, and/or by direct physical damage to the pest itself inflicted by the tillage machinery (Dent 2000). It is often an important method of weed control in many crops, and can assist with insect control in certain instances as well.

Cultural weed management: In addition to being a pest themselves, weeds can serve as habitat for many other types of pests. Disking, mowing, flaming (**Figure 8-3**), or hand weeding are examples of cultural controls to keep weed populations in check, and thus reduce or eliminate habitat for other pests.

Figure 8-3 Row crop weed flamer.
Photo: http://www.flameengineering.com/Row_Crop_Flamers.htm

Crop Rotation: Crop rotation, the practice of growing a series of dissimilar crops in a field over sequential seasons, can also seriously hinder a pest's survival, if the pest is dependent on the availability of resources of a specific crop upon its emergence. It is limited to non-perennial crops, with host specific pests.

Sanitation practices: Removal of pest habitat can also include general sanitation practices, such as the destruction of all plant and weed material left after harvest that could serve as potential habitat for the pest.

Timing of harvest/planting: Finally, the timing of the harvest or the planting of the commodity can greatly limit the availability of resources needed by the pest, and/or prevent impact by the pest during critical life cycle periods of the commodity.

8.3.2 Effectiveness as a BMP

- Preventive

Disking, cultural weed management, crop rotation, general removal of pest habitat, and timing of harvest and/or plantings can be effective preventive BMPs for reducing the need for pesticides if the pest populations can be lowered to a level where a pesticide application is not needed. As with other preventive BMPs, however, many studies report only the change in abundance of pests, but not whether the reduction in numbers was significant enough to replace the need for pesticide.

Disking*:* In the text book Insect Pest Management, David Dent (2000) provided a number of references to studies that reported reductions in pest populations as a result of disking: two grasshopper pests (*Kraussaria angulifera* and *Oedaleus senegalensis*) showed reduced numbers of eggs and nymphs after a field was disked; a sunflower seed weevil's (*Smicronyx fulvus*) population was reduced by 29-56% with a mould-board plough and by 36-39% with a chisel plough; another sunflower pest's (*Dectes texanus*) population was reduced by 73.5% with a disk plough and 39.7% with a sweep plough; a peppermint pest's (*Fumibotys fumalis*) population was reduced by 79-83% after strip tilling; and there was a reduction in the black cutworm (*Agrostis ipsilon*) in corn through disking or a combination of disking and crop rotation. While promising, these results do not clarify whether the pests were reduced to a level preventing the need for pesticide use, and thus the effectiveness of disking as a preventive BMP remains unclear.

Furthermore, disking and other forms of tillage are increasingly associated with a number of environmental problems, such as higher carbon efflux, nitrogen leaching, denitrification losses, soil crusting, loss of soil tilth, increased runoff, and increased erosion (Calderon and Jackson 2002, PSU 2008). As a result, conservation tillage and no-till practices are progressively being advocated as a replacement BMP for conventional tillage and disking. Given the potential environmental tradeoffs associated with conservation tillage in the form of increased herbicide use and leaching (see conservation tillage section), the advantages and disadvantages associated with tillage practices must be evaluated within the unique environmental and management characteristic framework of each grower in order to choose the most effective BMP.

Weed management: The efficacy of cultural weed management practices such as mowing, disking, flaming, or hand weeding is often highly dependent on the weed varieties and the commodity. Given that many herbicides can harm the commodity if not adequately selective, the use of cultural practices may often be mandatory within a certain proximity of the crop plants. The size and spacing of the crop plants may dictate which cultural practice is used. In addition, the species of weeds present in the field will largely determine which practices are chosen, as there is significant variation in the potential of different weeds to succumb to the different cultural practices.

Timing of weed management is also a concern for certain insect pests. If the weeds serve as habitat for a pest, then the grower must consider the impact on the commodity if the mowing or other removal of the weeds will result in the pest fleeing the weeds and infesting the commodity. In some cases, it may be necessary to ensure that the pest living in the weeds is destroyed before or during the weed management, to avoid simply replacing a weed competition problem with an insect pest problem.

Crop Rotation*:* Crop rotations are often used to reduce pests and diseases in potatoes, cereals, legumes, sugar beets, soybean, corn, oats, and wheat, among others. In general, this BMP is most effective for host specific pests with limited dispersal ranges. By depriving the pest of its host for one or more seasons, populations of many pests can be significantly reduced. Rotational crops can be selected to deprive an insect pest of its host for a season, or a crop can be selected that is able to out-compete weeds or produce an alleleopathic effect to diminish weeds (Strand 2000). However it is possible in some cases for pests to adapt to crop rotation systems, by extending diapause periods to avoid seasons of non-host plants (Diver et al. 2008).

There are numerous examples of crop rotations that assisted in pest management, such as the control of the Colorado potato beetle (*Leptinotarsa decemlineata*) in a potato-wheat rotation, where the rotation allowed for a delay of the pest infestation to a less critical period of commodity development (Dent 2000). In addition, Sorghum sudangrass grown following either potato or cucumber reduced root-knot nematodes to the same level as one application of nematicide (Kratochvil et al. 2004). Xiao et al. (1998) found that rotating cauliflower with broccoli and incorporating broccoli residues can manage verticillum wilt in cauliflower. The distance between crops created by rotations on adjacent fields can be used to manage the Colorado potato beetle, if distances are greater than 400 meters, according to Sexson and Wyman (2005). Kabaluk and Vernon (2000) determined that crop rotation in potato reduced the insecticidal treatments needed for tuber flea beetles by 4.2-7.3% while maintaining the economic value of the crop. In a study conducted in South Africa, Flett and McLaren (2001) found that corn ear rot was effectively reduced by wheat, soybean, and peanut as crop rotations, but not by sunflower. For the most part, however, very little information is available as to whether the crop rotation was sufficient to replace the need for pesticides, thus providing little information regarding its efficacy as a BMP.

Sanitation*:* Additional methods of removal of pest habitat include sanitation practices such as the destruction of mummy nuts in various nut crops after harvest, which was shown to reduce navel orangeworm damage, especially when the nuts were shredded (Sibbett and van Steenwyk 1992, Higbee and Siegel 2009), or the removal of pruned wood and weed habitat, such as in the 'plough-down' destruction of cotton stalks and plant residues implemented region wide in the Imperial Valley of California (Chang-chi et al. 1996, Grefenstette et al. 2008). The shredding and destruction of cotton plants has resulted in 75 to 90% mortality of the pink bollworm, according to various studies (Vincent et al. 2003).

Timing*:* Timing of harvest and/or planting has been shown effectively reduce pest impacts in various crops. For many commodities, plant growth regulators such as ethephon (Ethrel^{R}) can promote earlier maturation, coloration, or abscission. Earlier harvests can sometimes reduce or eliminate a pest infestation. A study with walnuts showed early, ethephon-induced harvests with only 0.5% navel orangeworm infestation as compared to 2.6% in the normal harvest, and 11.7% in a delayed harvest (Sibbett et al. 1974). Similarly, cotton growers induce early harvests with diuron defoliant products, often in an effort to harvest before rains begin. However, the early harvest can prevent late season pest infestations as well. The environmental benefits of any pesticide reductions due to the elimination of late season pest infestations needs to be balanced by the use of the harvest inducing agent - both ethephon and diuron are associated with various environmental risks.

Similar to early harvests, early plantings of crops can assist in reducing pest pressure, specifically weeds. Crops planted early have an advantage in competing with weeds compared to those planted later after weeds have already been established. In addition, varying the planting time of a crop can create asynchrony between the stages of the crop life cycle and that of the pest, which can disrupt colonization, reproduction and survival of the pest (Dent 2000).

Delayed plantings can also be effective. For fall harvest cucurbits, growers can keep the fields free of cucurbits during the early season to prevent a first generation of cucumber beetles and squash bugs, and thus significantly reduce pest damage on the late summer/fall crop (Diver and Hinman 2008).

8.3.3 Representative pesticides and commodities

For the pests treated by the five representative pesticides in the seven representative commodities in this study, disking was recommended by UCIPM for the cutworm in alfalfa and tomatoes, the weevil in cotton, the armyworm and flea beetle in lettuce, plant bugs in walnuts, and weeds in almonds, cotton, grapes, and walnuts. For weed management in particular: cutting, grazing or mowing was recommended by UCIPM for alfalfa, almonds, and grapes; flaming or hand-weeding was recommended for almonds, cotton, grapes, and walnut; and timing of planting was recommended for alfalfa. Weeds were not included as a pest in the analysis of lettuce or tomato, since none of the representative pesticides were used on them, anddiuron, the only representative herbicide, is harmful to these two commodities. However, many cultural weed management controls are advised by UCIPM, such as crop rotation and attention to irrigation timing for lettuce, and crop rotation, sanitation of tools, and solarization for tomatoes.

Crop rotation was recommended for flea beetles and weeds in tomatoes, and for weeds in lettuce. Sanitation and general removal of pest habitat was recommended by UCIPM for cutworm and mites in alfalfa; navel orangeworm in almonds and walnut; aphid, bollworm, cotton leaf perforator, cutworms, lygus, thrips, weevil, and whitefly in cotton; cutworm and leafhopper in grapes; aphid, armyworm, flea beetles and whitefly in lettuce; and cutworms, leafminers, stinkbugs, and whitefly in tomatoes.

If these BMPs were sufficiently effective, they could act as a replacement for applications of bifenthrin, chlorpyrifos, malathion, and diuron, thus reducing negative impacts to most aspects of the environment. However, as with most preventive BMPs, the reported reduction in pest populations was not conclusive as to whether a pesticide application could be avoided.

8.3.4 Helpful links and tools

Understanding the life cycle stages of pests and their host specificity could aid in determining the best timing to increase the efficacy of many BMPs and the best crops to use in crop rotations. The following website lists detailed life cycle information for pests:

UC IPM Online Pest Management Guidelines:
(http://www.ipm.ucdavis.edu/PMG/crops-agriculture.html)

8.3.5 Costs

Table 8-6 shows the inflation adjusted 2008 cost of various cultural practices such as disking fields and removing pest habitat for each of the representative commodities, taken from recent cost and return studies from the Agricultural and Resource Economics Department, University of California, Davis. In summary, disking costs averaged $16/acre, weeding $61/acre, and other types of habitat removal around $146/acre.

For the commodities that benefit from crop rotations, there are often economic benefits in the form of increased pest management, improved soil fertility if legumes are in the rotation, and the ability to spread production and market risk over multiple crops. Tomatoes and lettuce were the only representative commodities for which UCIPM specifically recommended crop rotation. Cost data was not readily available for those crop rotation suggestions.

Weeding by flaming requires an investment in a flamer, which ranges in cost from $1,200 to $1,900, and around 8-10 gallons of propane gas per acre. In 2007, the representative cost of propane was $1.87/gallon, so assuming a need of 10 gallons per acre, weeding by flamer would be around $19/acre, which is economically competitive with certain herbicides (Sullivan 2001, NPGA 2007).

For BMP comparative purposes, a grower practicing habitat removal would likely see an average increase in costs of around $69 per acre, which is the average cost of disking, weeding, and other types of removal (**Table 8-6**). All other production costs are assumed to be held constant, although this assumption is unlikely to be true in the case of weed management, where herbicide use may decrease if disking or flaming is used.

Table 8-6. Costs of cultural preventive BMPs for each representative commodity. Data from recent cost and return studies, Agricultural and Resource Economics, University of California, Davis.

Representative Commodities	BMP	Specifics	Cost ($)/acre
Alfalfa[a]	Disk	Disking 2x	20
Almond[b]	Disk	Disking 2x	13
	Habitat Removal	Pruning/shredding brush	180
		Sanitation: mummy removal	161
	Weeding	weed: mow 6x	38
Cotton[c]	Disk	Disking2x	16
	Habitat removal	chop stalks	19
	Harvest timing	defoliate	31
	Variety choice	seed technology fee (Bt and roundup)	49
Grapes[d]	Disk	Disking 2x	18
	Habitat removal	Pruning/shredding brush	480
	Weeding	weed: mow 3x	26
Lettuce[e]	Disk	Disking 2x	16
	Weeding	Hand weed 2x	117
Tomatoes[f]	Disk	Disking 2x	19
	Habitat removal	Sanitation: mow/shred plants, disk residue	25
	Weeding	Weeding: cultivating and hand hoe	95
Walnuts[g]	Disk	Disking 2x	10
	Habitat removal	Pruning/shredding brush	29
	Weeding	weed: mow 5x	26

(Mueller et al. 2008)[a] (Duncan et al. 2006a)[b] (Meister 2004a)[c] (Peacock et al. 2007a)[d] (Meister 2004b)[e] (Stoddard et al. 2007)[f] (Grant et al. 2007)[g]

Costs adjusted for inflation to reflect probable 2008 costs (http://www.westegg.com/inflation/)

8.4 Barriers

8.4.1 Definition/Background

The impact of pests on a commodity can be suppressed through disruption of the pest's access to the crop. Barriers such as water filled ditches, or strips of a border such as heavy aluminum foil, row covers, or netting can stop certain pests from finding and/or accessing the crop plants.

8.4.2 Effectiveness as a BMP

- **Preventive**

Water trenches, fences, or aluminum foil barriers are likely to be most effective against ambulatory land-based pests. The effectiveness of these barriers may ultimately be decided by a combination of the construction of the barrier and the determination and capabilities of the pest.

A portable trench barrier was reported to be as effective as insecticides in protecting tomatoes from the Colorado potato beetle (*Leptinotarsa decemlineata*) in Canada (Hunt and Vernon 2001). A study by Appropriate Technology Transfer for Rural Areas (ATTRA) (Kuepper 2003) and a study by Boiteau et al. (1994) both found that a plastic lined trench surrounding a potato field reduced the beetles by nearly half. Row covers (**Figure 8-4**) can also prevent pests from reaching a crop (Adam 2006, Diver and Hinman 2008), however they can be very costly on a large scale and difficult to work with.

Figure 8-4. Row covers.
(IPM, Michigan State University)

8.4.3 Representative pesticides and commodities

UCIPM recommends barriers of water trenches or aluminum foil for saltmarsh caterpillars in lettuce and tomatoes. Therefore, if these BMPs were effective, they could potentially replace applications of bifenthrin, thus reducing VOCs, and toxicity to humans, birds, aquatic species, natural enemies of pests and other arthropods in lettuce and tomatoes.

8.4.4 Helpful links and tools

The National Sustainable Agriculture Information Service, Appropriate Technology Transfer for Rural Areas (ATTRA) website lists a number of pest specific publications with advice on barriers as cultural controls. (http://attra.ncat.org/)

8.4.5 Costs

Trench: Boiteau et al. (1994) reported that the cost of a Colorado potato beetle trench was recovered through the elimination of just one insecticide application to a potato field around four hectares in size. This estimate is rather vague, given there are numerous pesticides with a wide range of costs that can be used to treat for this beetle. However, based on the average label use rates of four pesticides commonly used to treat Colorado potato beetle in potatoes (Asana, Sevin, Baythroid, and Thiodan), the cost of the trench could be estimated at around $82 to $202 for the four hectare field (average $127). (Boiteau et al. 1994, Bessin 2004, CDMS 2009, De Moura 2009). Misener et al. (1993) developed a trenching tool, the 'beetle excluder', which was estimated to cost around $3000 to construct. Assuming the Colorado potato beetle barrier does not span the circumference of the field, the cost estimates for the four hectare farm are potentially the same as for a 50 acre farm.

Row covers: Johnny's Selected Seeds sells a 118" x 250'Agribon+ AG-15 Insect Barrier row cover for $45. *(*www.johnnyseeds.com/) Thus, approximately 17 units would cover an acre, at around $765/acre.

For BMP comparative purposes, the cost of the potato beetle barrier would have an installation cost of around $3000 for the machinery, which would be about $60 per acre for a 50 acre farm. If the implementation cost range of $82 to $202 is also divided by 50 acres, the trench installation would range from around $2 to $4 per acre, resulting in a total cost including machinery of $62 to $64 per acre.

Installation costs for row covers would be around $765 per acre. The cost of labor to install and maintain the row covers was not available.

Therefore, if a grower was to implement barriers as a BMP, costs would likely increase from $60 to $765 per acre, averaging around $423 per acre in the first year. All other production costs were assumed to remain constant; however this may be an incorrect assumption if use of a barrier reduces the need for pesticides, and therefore pesticide costs.

Yearly maintenance costs were more difficult to estimate. While studies reported that maintenance on the beetle barrier was not necessary during the season, it was unclear what the lifespan of a barrier was, or whether it would need to be re-constructed each year. Similarly, data on the labor for installation and maintenance of row covers was not available. It is likely, however, that row covers can be re-used for more than one season if they are cared for properly.

8.5 Optimal Fertilization/Irrigation

8.5.1 Definition/Background

Fertilization: Many pests are attracted to overly-fertilized crops. These plants offer concentrated sources of nitrogen (N) for the pest to exploit, often producing large amounts of succulent new growth and/or extending the growing season and thus the length of time nutrients are available to the pest (Altieri and Nicholls 2003, Zhong-xian et al. 2007). Thus, optimal fertilization can play an important role in producing plants that are less attractive to its pests.

Irrigation: Irrigation can serve as both a mitigative and preventive BMP. As a preventive BMP, irrigation can affect two aspects of pest management that can potentially influence the need for pesticide use. First, irrigation plays a role in the management of the water stress level of the crop, which has been shown to influence pest pressure and/or damage. Second, the method of irrigation can potentially disrupt the pest's life cycle, if it creates a flooded environment that is able to drown soil dwelling pests.

As a mitigative BMP, the method of irrigation can influence environmental impact on surface and/or groundwater, through runoff or leaching, respectively. Factors such as the type of irrigation system, water flow rate, and timing all play important roles in determining the amount of runoff or deep percolation which can potentially move pesticides offsite.

Barbash and Resek (1996) have shown that wells less than 50 feet deep in unconsolidated aquifers of areas with irrigated agriculture were around twice as likely to have pesticide contamination than equally shallow wells in non-irrigated areas. Despite California's groundwater levels being nearly twice as deep (an average of 106 feet in 2007) (USGS 2009), many pesticides have been detected in groundwater supplies. Determining the correct amount of water to meet the crop's needs, without creating an excess that can move pesticides offsite via runoff or leaching, can be quite technology-intensive, however.

There are three main types of irrigation methods: surface, sprinkler, and microirrigation.

Surface: Soil is the transport medium and gravity is the driving force for surface irrigation. Water enters furrows or border checks at the top of a field or orchard, and, as it flows down the field, it infiltrates the soil. There is thus often intentional runoff in order to ensure adequate infiltration at the lower end of the field. Non-uniform soil properties can greatly affect the water distribution, resulting in over-irrigation in many regions of the field (Schwankl et al. 2007a). Frequently a tailwater return flow system will be used to pump runoff back to the top of the field. However, there can be significant leaching of pesticides from these ponds into the groundwater (Holden 1986). Thus, there is often significant runoff and deep percolation with surface irrigation.

Types of surface irrigation include basin irrigation, border strip irrigation, continuous flood (basin paddy), ponding (fill and drain), furrow irrigation (including systems with cablegation and surge flow; **Figure 8-5**), corrugations, and contour ditches (wild flood).

Figure 8-5. Surface Irrigation
Photo: College of Agriculture and Life Sciences, North Carolina State University

Sprinkler: Sprinkler irrigation systems deliver water through pressurized pipes to nozzles, jets or perforated pipes extending from them. Sprinkler systems can apply water evenly and can result in better uniformity than surface irrigation. Sprinklers can be used to irrigate most crops, and can generally be used on any topography and most soil types. However, sprinklers can keep foliage and branches wet for prolonged periods, which can result in diseases and/or discoloration in certain crops. A sprinkler irrigation system that is well-designed and properly operated will have little or no runoff.

Examples of sprinkler systems include hand move portable or lateral move portable systems (end tow lateral, side roll/wheel line systems, side move lateral, traveling gun system and rotating boom system), center pivot system, linear move (lateral move) system, solid set and permanent set system, and under-tree orchard sprinkler systems. The differences in these systems include the method of moving the sprinkler and the geometry of the area irrigated.

Microirrigation: Microirrigation systems allow for the distribution of water directly to plant root zones (**Figure 8-6**). They result in efficient and uniform application of irrigation water and maintenance of soil moisture. These irrigation systems can be used on row and orchard crops on almost all soils and topography. Runoff is either reduced or eliminated and deep percolation is reduced, thus ensuring that most water is directly used by the plants.

The main classifications of microirrigation systems are surface or subsurface drip irrigation and microspray or microsprinkler systems.

Figure 8-6. Micro Irrigation.
Photos: Brigham Young University, Texas A&M, UCIPM

In addition to the choice of irrigation system, scheduling and water flow rate are important components to reducing or eliminating pesticide runoff and/or deep percolation to groundwater. In order to avoid over-irrigation, the grower must consider irregularities in water distribution, the soil water capacity of the field, the evapotransporation, the depth of the root zone, and the crop's rate of water consumption, among other variables.

8.5.2 Effectiveness as a BMP

- Preventive:

Optimal fertilization: Altieri and Nicholls (2003) advocates the hypothesis that crop plants fertilized with organic amendments have less insect damage than crops fertilized with synthetic fertilizers, which typically have higher nitrogen concentrations. In support of this hypothesis, the paper cites numerous international studies where pest infestations were lower in organically fertilized fields compared to conventional fields. However, while the growers using organic soil amendments had lower pest abundance and did not treat with pesticides, it is still unclear whether the pest abundance was lowered to a threshold where a non-organic grower would refrain from pesticide use. Hence it is difficult to predict the efficacy of optimal fertilization as a preventive BMP. In addition to potentially reducing pesticide use, optimal fertilization also reduces excess nitrogen pollution, which can end up as nitrate in groundwater and surface water bodies.

Optimal irrigation: The efficacy of optimal irrigation as a preventive BMP is not clear. Certain studies have shown that well-watered plants have more pest damage than those with high water stress, as in cases of aphid or mite in cotton and potato (Sadras et al. 1998, Nguyen et al. 2007). However, other studies have shown that intermittent water stress can favor pests

(Huberty and Denno 2004). Studies in almonds have conflicting results, with some authors claiming that spider mites have higher population numbers when the trees are stressed (Youngman and Barnes 1986), while other studies have concluded that the mite populations do not vary based on the water stress level (Goldhammer et al. 2006). As with other preventive BMPs, it is unclear whether any reduction in pest abundance based on the amount of water supplied to the plant is sufficient to replace need for pesticides.

- Mitigative

Optimal Irrigation: In general, surface irrigation has the greatest potential for runoff. Surface irrigation is also likely to have the deepest percolation, and thus potential for pesticide leaching to groundwater. Usually little to no runoff is associated with sprinkler and microirrigation systems that are set up and managed correctly. The more even distribution of water using these systems can prevent excessive water amounts from accumulating and moving to groundwater.

While sprinkler or microirrigation systems are the preferred irrigation BMP, there are certain practices that can lessen the impacts of surface irrigation. For example, the offsite movement of pesticides attached to sediment can be reduced by slowing the velocity of the flow - the faster the water moves over the soil, the more silt it is likely to pick up and carry offsite in suspension. An Imperial County total maximum daily load (TMDL) BMP handbook recommends that drain water velocity be kept below 36 feet per minute to avoid offsite movement of sediments. It suggests this can be achieved through use of dams of different materials and drain boxes (Kalin 2003). In addition, it suggests that water flow can be slowed by creating drainage ditches with pan shaped, rather than V-shaped bottoms. However, a study by Moore et al. (2008) concluded that vegetated V-shaped ditches were much more efficient in reducing California diazinon and permethrin concentrations based on lower pesticide water half-distances (the distance it takes to reduce initial concentrations by 50%).

In general, the goal of an efficient irrigation system is to limit the amount of water to just what the crop needs, avoiding any excess that may move offsite, transporting pesticides in the process. The timing of irrigation can also be important in reducing runoff or deep percolation. The longer the time period between the pesticide application and the irrigation event, the more time the pesticide will have to volatilize or degrade, thus potentially reducing the amount of pesticide available for offsite movement via runoff or deep percolation (see pesticide application section, timing, water).

8.5.3 Representative Pesticides and Commodities

UCIPM recommends optimal fertilization and/or irrigation as a pest management practice that could function as a preventive BMP for the following pest/commodity combinations: mites in almonds; aphids, bollworms, mites, tobacco budworms, and whiteflies in cotton; mites and vinegar flies in grapes; aphids and whiteflies in lettuce; and mites in walnuts. Flooding is recommended for cutworms in alfalfa, bollworms in cotton and ants and cutworms in grapes.

If these practices were effective as pest controls, applications of chlorpyrifos, bifenthrin, diazinon, and malathion could potentially be reduced or eliminated, thus reducing negative impacts to all of the environmental components analyzed. However, as with the other preventive BMPs, it is unclear whether reductions in pest numbers are sufficient to replace need for pesticides.

In contrast, the mitigative qualities of efficient irrigation are more concrete. If a grower was able to supply only enough water to the crop to meet its needs, runoff and leaching could be virtually eliminated, with all water being taken up by the plant. Thus efficient irrigation as a BMP can greatly mitigate the environmental impact of all representative pesticides transported offsite via runoff or leaching, either dissolved in the water or attached to sediment. Achieving irrigation efficiency can be difficult, though, as the variables that affect efficiency are non-uniform across a field. Because there is risk of damaging the crop through under-watering, most growers will choose to err on the side of over-watering to prevent this risk.

8.5.4 Helpful links and tools

The following websites can assist in implementing optimal fertilization and irrigation:
Cornell Nutrient Analysis Laboratory (http://cnal.cals.cornell.edu/)

California Irrigation Management Information System (CIMIS), Department of Water Resources, Office of Water Use Efficiency offers a number of irrigation efficiency tools, such as links to irrigation consultants, mobile irrigation labs, software to assist in developing a water budget and irrigation schedule: (http://www.cimis.water.ca.gov/cimis/infoIrrOverview.jsp)

Total Maximum Daily Load (TMDL) voluntary compliance program website for the Imperial Valley offers ideas and photos of various irrigation BMPs (http://www.ivtmdl.com/)
TMDL training video in both English and Spanish (http://www.ivtmdl.com/video.php)

University of California, Agriculture and Natural Resources Specialist and Farm Advisor Publications: There are many free publications on BMPs for reducing pollution from irrigation distributed on the UCANR website
Irrigation: (http://ucanr.org/freepubs/freepubsub.cfm?cat=11&subcat=16)
Farm Water Quality Planning Series:
(http://ucanr.org/freepubs/freepubsub.cfm?cat=11&subcat=15)

The Coalition for Urban/Rural Environmental Stewardship (CURES) manual on irrigation scheduling: (http://www.curesworks.org/bmp/irrigScheduling.pdf)

8.5.5 Costs

The Coalition for Urban/Rural Environmental Stewardship (CURES) estimates the cost for a grower or contractor installed drip or microirrigation system to be between $800/acre and $1800/acre, covering installation, maintenance for the life of the system, and the cost of a new pump at $100/acre (CURES 2007).

In addition, as a general estimate, costs for fertilization and irrigation of the representative commodities, as presented in recent Cost and Return studies developed by the Department of Agricultural and Resource Economics, University of California, Davis, are listed below in **Tables 8-7 and 8-8,** with all costs adjusted for inflation to 2008 for comparative purposes. These costs are more likely to be 'typical' than 'optimal', however. In addition, not all practices are represented; there may be more optimal practices for a commodity that were not listed in the tables due to a lack of availability of recent studies.

Fertilization costs ranged from $24 to $299 per acre, with an average of $108 per acre (**Table 8-7**). The costs presented in **Table 8-7** include labor, fuel, lube, repairs, material costs, and/or custom/rent costs when applicable. Initial crop establishment costs are not included. Data comparing the costs of chemical fertilizers to those of the optimal fertilization methods mentioned in section 8.5.2, such as organic amendments, were not available. Altieri et al. (2003), and studied cited therein, suggest that pest levels were lower in crops fertilized with organic amendments. Thus, their use could potentially lead to indirect savings from decreased pesticide use.

Cost estimates for installing and using various irrigation systems in the representative crops are presented in **Table 8-8**. Different studies included different types of costs, so values should be treated as 'best estimate' comparisons, with the understanding that a study may not be fully inclusive of all irrigation costs. The costs for surface irrigation are compared with microirrigation and sprinkler irrigation in **Table 8-9**. The total cost of surface irrigation ranged from $100 to $220 per acre (average $163 per acre). The total cost of sprinkler irrigation ranged from $120 to $352 per acre (average $250 per acre). Finally, the total cost of microirrigation was the highest, from $316 to $418 per acre (average $359 per acre).

For BMP comparative purposes, if a grower was to switch from surface irrigation to sprinklers or microirrigation, total cost would increase on average by $87 per acre to $196 per acre, with an average increase of $142 per acre. All other production costs are assumed to remain constant. This assumption may be incorrect, however, if irrigation or fertilization efficiency as a BMP is able to reduce the need for pesticides, and hence pesticide costs.

Table 8-7. Operational costs: fertilization.
From recent Cost and Return studies published by the department of Agricultural and Resource Economics, University of California, Davis.

Representative Commodities	Specifics	Cost ($/ per acre)
Alfalfa	Tissue sample + 11-52-0, 1x per 2 years: 50% cost[a]	42
	Totals	42
Almond	Leaf samples[b]	2
	Hull samples[b]	1
	Spray tree row (Solubor) [b]	15
	Potassium Sulfate[b]	101
	Totals	118
Cotton	Cultivate and sidedress: 100lb N UAN32[c]	60
	Water run fertilizer[c]	15
	Totals	75
Grapes	N through drip UN32[d]	24
	Totals	24
Lettuce	Fertilize and furrow out 2x 120lb UAN32[e]	85
	Water run fertilizer 100lb UAN32[e]	43
	Totals	128
Tomatoes	Soil and tissue analyses[f]	4
	Multiple fertilizers[f]	295
	Totals	299
Walnuts	N through sprinklers UN32[g]	72
	Leaf samples[g]	2
	Totals	74

[a] (Mueller et al. 2008) [b] (Duncan et al. 2006a) [c] (Meister 2004a) [d] (Peacock et al. 2007a) [e] (Meister 2004b) [f](Stoddard et al. 2007) [g](Grant et al. 2007)
Costs adjusted for inflation to reflect probable 2008 costs (http://www.westegg.com/inflation/)

Table 8-8. Irrigation system costs for representative commodities. Costs are rounded up.

Representative Commodities	Specifics		Installation $ per acre	Irrigation $ per acre	Total
Alfalfa					
Irrigation system (underground pipes w/ alfalfa valves)[b]			38[a]		
Surface irrigate 10x[b]				182	
Alfalfa	Surface	Totals	38	182	220
Wheel line irrigation + Center pivot irrigation [c]			32[a]		
Irrigate 6x[c]				88	
Alfalfa	Sprinkler	Totals	32	88	120
Almond					
Flood irrigation system[d]			37[a]		
Flood irrigate 10x[d]				62	
Almond	Surface	Totals	37	62	100
Pumping system plus micro-sprinkler system[e]			147[a]		
Irrigation frost protection[e]				11	
Irrigate 56x[e]				259	
Almond	Microirrigation	Totals	147	271	418
Pumping system plus low volume sprinkler system[f]			122		
Irrigation frost protection[f]				13	
Irrigation[f]				216	
Almond	Sprinkler	Totals	122	2229	352
Grapes					
Drip irrigation system[g]			114[a]		
Drip irrigate[g]				201	
Grapes	Microirrigation	Totals	114	201	316
Tomatoes					
Furrow: make ditches [h]			3		
Irrigate (water and labor) [h]				164	
Close ditch and drag[h]				3	
Tomatoes	Surface	Totals	3	167	170
Walnuts					
Micro-sprinkler system, pump/well [i]			127[a]		
Irrigate (water and labor) [i]				217	
Walnuts	Microirrigation	Totals	127	217	334
Sprinkler irrigation system: pull hoses, pump, well [j]			157[a]		
Irrigate 4x [j]				120	
Walnuts	Sprinkler	Totals	157	120	277

[a] Capital recovery cost - equivalent to the annual payment on a loan for the investment with the down payment equal to the discounted salvage value. ((Purchase Price – Salvage Value) x Capital Recovery Factor) + (Salvage Value x Interest Rate)
[b] (Mueller et al. 2008) [c](Orloff et al. 2007a) [d](Duncan et al. 2006a) [e](Duncan et al. 2006b) [f](Connell et al. 2006) [g](Meister 2004a) [g](Peacock et al. 2007a) [h](Stoddard et al. 2007) [i](Grant et al. 2007) [j](Elkins et al. 2007). Costs adjusted for inflation to reflect probable 2008 costs (http://www.westegg.com/inflation/ and http://www.usinflationcalculator.com/ for 2009 data)

Table 8-9. Comparing costs: surface irrigation versus microirrigation or sprinklers (summary of data in Table 8-8).

	Installation $ per acre			**Irrigation $ per acre**			**Total Cost $ per acre**		
	min	max	avg	min	max	avg	min	max	avg
Microirrigation	110	142	125	194	261	221	304	403	346
Sprinkler	31	151	100	85	221	141	116	339	241
Surface	3	37	25	60	175	132	96	212	157
Difference between Microirrigation or Sprinklers and surface									
Microirrigation	107	105	99	134	86	89	208	191	189
Sprinkler	28	114	75	25	46	9	20	127	83

8.6 Trap plants, intercropping, and cover crops

8.6.1 Definition/Background

Trap Plants: Certain plants have characteristics that make them especially attractive to various pests. These plants can serve as traps for pests, enticing the pest away from the commodity. Once the pests are concentrated in one area, they can potentially be destroyed.

Intercropping and cover cropping: Intercrops and cover crops can be trap plants, natural enemy habitat plants, soil amending plants, and/or plants known to be undesirable to a specific pest. They can be annuals or perennials, although annuals are more likely to be used with annual primary crops. Often, they are mowed down at some point, leaving their residue to act as a mulch to suppress weeds.

As a preventive BMP, they can either serve as a preferred alternative host, or prevent the pest from easily locating the main crop plants, in contrast to monocultures, where the pest can sequentially move from one crop plant to the next.

Figure 8-1. Intercropped flower strips in celery field as habitat for beneficials (Photo: Eric Brennan, UC SAREP)

Depending on the plant species used to intercrop or cover crop a field, further pest protection can occur from increased biological control (**Figure 8-7**) or from a reduction in weeds.

Intercrops and cover crops can also function as a mitigative BMP, since the plant species can be chosen for their ability to stabilize soils, prevent erosion, increase infiltration, and reduce runoff.

However, while a cover crop or interplanted crop can potentially suppress weeds, increase natural enemy populations, reduce soil erosion, and add organic matter and nitrogen to the soil, it can also compete with the crop for soil moisture and resources, and in some instances, can increase weed and pest problems. Growers are advised to test a few rows before sowing large areas, in order to judge the cover crop performance in their field. It is also important to choose species that can perform well under the grower's irrigation practices, tillage methods, nitrogen needs, frost conditions, and harvesting practices (Ingels et al. 1996, Ingels 2009).

8.6.2 Effectiveness as a BMP

- Preventive

Trap crops: The effectiveness of trap crops as a preventive BMP is not only determined by how well the trap works in attracting the pest away from the commodity, but also by whether pesticide use is actually reduced, since it is possible that the grower will use pesticide on the trap crop to control the pest. However, given that the pest is concentrated into a smaller area of the trap crop rather than dispersed throughout the field, pesticide use may be lessened compared with fields without trap crops.

Mensah and Sequeira (2004) lists studies where interplanted trap crops such as lucerne for mirids and chickpea/pigeon pea or lucerne, lablab, and pigeon pea for *Helicoverpa* spp. have been successful in cotton, diverting pests away from the cotton into smaller areas where they could be controlled. However, Castle (2006) reports that the use of cantaloupes as a trap crop for cotton reduced populations of whitefly (*Bemisia tabaci*), but not below economic thresholds, signifying that pesticides would still be needed. Tillman (2006) and Tillman and Mullinix (2004) found, respectively, that sorghum was successful as a trap crop for southern green stink bug and corn earworm in cotton. Swezey et al. (2007) reports the successful use of alfalfa as a trap crop to protect strawberries from western tarnished plant bug (*Lygus hesperus* Knight), with control of the plant bug through a tractor mounted vacuum system used on the trap crop of alfalfa, rather than pesticide. Javaid et al. (2005) found that transgenic Bt corn could be used successfully as a trap crop for soybeans against the corn earworm.

Intercropping and cover crops: The use of intercropping and cover cropping has been shown to provide effective protection of many crops, either through making it difficult for the pest to locate the crop plants, or improving on-site habitat for natural enemies. Hooks and Fereres (2006) concluded that barrier crops planted in multiple commodities could reduce aphid-transmitted viruses. Mensah and Sequeira (2004) summarized a number of international studies reporting success in controlling pests through intercropping other plants with oats, cotton, corn, melons, peaches, cassava, beans, peanuts, tomatoes, and cole crops. Hooks and Johnson (2003) reviewed many successful international experiments with intercropping in cruciferous crops. Prather et al. (2000) found that older stands of alfalfa interplanted with grasses reduced weeds and alfalfa weevil below pesticide threshold conditions, while increasing overall production. Johnson et al (1993) found that mowed hairy vetch and rye cover crops controlled weeds more effectively than soybean stubble when no herbicides were used in reduced-till corn. However, they also noted that corn height and population were reduced by hairy vetch and rye covers and that corn yield was reduced for plots using rye as a cover crop. Another study on soybean with a rye cover crop determined that the rye residue reduced weed density by 9% and 27% and weed biomass by 19% and 38% as compared with conventional tillage and no-till systems without cover crops (Reddy 2003). Finally, a Costa Rican study found that a ground cover of peanuts, cinquillo, and coriander in tomato fields could greatly mask the tomato from whitefly (*Bemesia tabaci*), which can transmit begomoviruses that affect yields (Hilje and Stansly 2008).

- Mitigative

Cover crops can be grown to stabilize the soil against wind and water erosion, which can prevent the offsite movement of pesticides adsorbed to sediment. They can also increase soil productivity, and can alter the porosity of the subsurface, which increases infiltration, and thus reduces runoff. However, while infiltration reduces the likelihood of surface runoff, it may increase the possibility of groundwater contamination (Munoz-Carpena et al. 2008).

Zhu et al. (1989) found that a winter cover crop in a soybean system in Missouri reduced runoff by 44% to 53%, and soil loss via erosion by 87% to 96%, however actual pesticide loss reductions were not measured.
One study on a California French prune orchard showed that, regardless of species, a cover crop in the orchard rows reduced total pesticide loading and total runoff volume by 50% (Werner et al. 2004). In contrast, a study by Sadeghi and Isensee (2001) found no statistically significant difference in runoff amounts and losses of herbicides between fields with and without a cover crop of vetch.

8.6.3 Representative pesticides and commodities

UCIPM recommends interplanting for alfalfa and cover cropping in grapes, almonds, and walnuts to reduce weeds. Therefore, if effective as weed suppressants, these BMPs could potentially replace applications of diuron, thus reducing impact to groundwater and sediment. In addition, certain arthropod pest populations could potentially be reduced if the interplanted or cover crop attracted natural enemies effective at controlling the pest biologically. Yet, it is unclear from the studies how often pest population reductions were sufficient to replace the need for pesticides.

In addition to preventive benefits, the use of cover crops to stabilize soil and increase infiltration could potentially reduce runoff of all representative pesticides in all representative crops. However, results of the studies analyzed in this report were variable, ranging from 0% to 53% reduction in runoff from fields with cover crops, at an average of 27%. Finally, care must be taken to prevent leaching to groundwater through any increased infiltration capacity.

8.6.4 Helpful links and tools

Appropriate Technology Transfer for Rural Areas (ATTRA) Intercropping Principles and Production Practices details the principles behind intercropping, as well as offers advice on spatial arrangement, plant density, timing considerations, productivity, and general management. (http://www.attra.org/attra-pub/PDF/intercrop.pdf)

ATTRA Companion Planting: Basic Concepts and Resources Guide provides a companion planting chart and system design recommendations (http://attra.ncat.org/attra-pub/PDF/complant.pdf)

ATTRA Overview of Cover Crops and Green Manures: Fundamentals of Sustainable Agriculture (http://attra.ncat.org/attra-pub/PDF/cover crop.pdf)

UC SAREP Cover Crop Resource Page: includes a database on the management of over 32 species of plants useable as cover crops as well as many papers and publications: (http://www.sarep.ucdavis.edu/ccrop/)

8.6.5 Costs

Prather et al. (2000) found the cultural costs of interplanted alfalfa and grass ($118/acre) to be less than alfalfa treated with herbicide ($150/acre). However, the net profit of the lower-quality mixed hay (net profit $52-128/acre) was less than pure alfalfa treated with herbicide (net profit $136/acre). This example identifies the key financial considerations when implementing cover crops, interplanted crops, or trap crops as a BMP: the costs and benefits will be very commodity-secondary crop-pest-specific. If the secondary interplanted, cover, or trap crop is not as profitable as the main commodity, or reduces profitability of the crop through competition, then any savings from pest control or soil amendments must be balanced against the opportunity costs of planting a monoculture or leaving the ground bare, as estimated earlier in **Table 1-3**.

For example, in a mini-review of cover crop biology put out by UC SAREP, certain cover crops were shown to reduce vine and orchard growth and vigor (Bugg 1995). The potential for lower yields must therefore be weighed against any pest control or soil benefits of the cover crop, trap crop, or intercropped plants.

An example of estimated costs for an annually planted cover crop of oats in the Central Coast region of California in 2003 is presented in **Table 8-10.**

For BMP comparative purposes, a grower planting a cover crop as a BMP would be expected to have a cost increase ranging from $57 to $191 per acre, with a representative cost of $171 per acre, compared to the equivalent acreage without cover crop (**Table 8-10**)**.** These estimates assume all other production costs are held constant, which is likely to be an incorrect assumption given that the use of a cover crop can affect pesticide use, irrigation efficiency, fertilizer needs, and yields, among other things.

Table 8-10. Estimated costs of annually planted cover crop. (Tourte et al. 2003b)

Annual Installation, Operations and Maintenance	**Estimated Costs ($)**		
	Low	**Representative**	**High**
Land Prep - Chisel 1X	5	5	5
Land Prep - Disk 1X	6	6	6
Drill Cover Crop Seed	33	50	61
Set Up Sprinklers & Irrigate	0	87	87
Mow - Flail	0	9	18
Disk - Incorporate Plant Materials 2X	11	11	11
Subtotal	56	169	189
Interest on Operating Capital @ 7.4%	1	2	2
Total Costs per acre	57	171	191

Costs adjusted for inflation to reflect probable 2008 costs (http://www.westegg.com/inflation/)

8.7 Synthetic Mulches

8.7.1 Definition/Background

In contrast to living mulches such as cover crop residues, synthetic mulches take the form of either plastic sheeting that can be used to control pests through soil solarization, or mirrored reflective mulches that disorient pests attempting to locate the crop.

Solarization is thought to reduce pest and weed pressure, while also enhancing certain physical and chemical characteristics of the soil through increased temperatures, thus improving yields in a number of different crops. Strip solarization is the method of installing plastic films over raised beds during the summer, and leaving the plastic in place as mulch for a fall crop that is planted directly through the plastic into the bed. Many solarization studies report long term beneficial effects, with increased yields and less pest pressure in following seasons as well.

Reflective metallic mulches can be useful for certain pests such as thrips, aphids, and whiteflies, which can become disoriented and unable to locate the plant. In contrast to solarization, the metallic nature of the mulch can sometimes reflect heat away from the ground, thus lowering soil temperatures, and slowing down seasonal development processes.

8.7.2 Effectiveness as a Preventive BMP

Solarization: Hasing et al. (2004) found that summer strip solarization with clear and black plastic mulches improved yield in lettuce and reduced weed density, which was four times higher in the non-solarized control plots. Stapleton and DeVay (1986) cited many studies of effective solarization, including control of southern blight and tomato fruit rot on tomatoes, and less disease in lettuce. As with most studies analyzed in this report for their efficacy as a preventive BMP, difficulty arises due to a lack of reporting whether the reduction in pests was sufficient to replace pesticide use. Some studies did imply that pesticide use was not needed, as was reported in a solarization study of lettuce in Brazil that found that the practice was roughly as effective as fungicides in controlling for the fungal diseases drop and bottom rot, and as effective as herbicides in controlling weeds (Patricio et al. 2006). In addition, Freeman et al. (1990) found that full soil solarization resulted in 100% elimination of viability of white root rot (*Rosellinia necatrix*) fungus, a disease of apple trees, compared to a 40% viability reduction in shaded solarized plots, when both treatments were compared to non-solarized plots

Reflective: Stapleton et al. (2002) found that the use of reflective mulches in cantaloupes grown in California reduced the number of aphids landing on the crop, thus delaying the onset of aphid-vectored diseases by around six weeks, and resulting in higher yields. In addition, Stapleton and Summers (2002) listed numerous other studies that have reported successful use of reflective mulches in various cucurbit crops (Kring 1969, Loebenstein and Raccah 1980, Brown et al. 1993, Stapleton and Summers 1997, Summers and Stapleton 1998, Caldwell and Clarke 1999, Summers and Stapleton

1999, 2002). Similarly, Riley and Pappu (2004) found that use of reflective mulch reduced thrips and thrips-vectored tomato spotted wilt virus when used with a resistant variety of tomatoes grown in Georgia, compared with different insecticide treatments. Smith et al. (2000) found that a reflective mulch decreased egg densities of whitefly (*Besmia argentifolii* Bellows and Perring) on organically grown beans in Florida compared to beans grown without the mulch. Rhainds et al. (2001) found that strawberries grown in New York with reflective mulch had reduced incidences of tarnished plant bugs (*Lygus lineolaris*) and increased yield compared to strawberries without mulch. However, it was unclear in these studies whether the decrease in pest populations eliminated the need for pesticides.

8.7.3 Representative pesticides and commodities

UCIPM recommends solarization for weeds in walnuts and grapes, thus potentially reducing use of diuron if the solarization is effective. Reflective mulch is recommended for aphid and whitefly in tomato, which if effective, could reduce applications of diazinon and bifenthrin. Lower use of diuron, diazinon, and bifenthrin could result in lower impacts to surface water, sediment, groundwater, air quality (VOCs), human health, and the health of aquatic and terrestrial wildlife.

8.7.4 Helpful links and tools

The following websites can assist in implementing mulches as a pest management strategy:

University of California Solarization Informational Website on passive solar disinfestation of soil, plants, and structural materials. Includes temperature maps, weed seed thermal death guidelines, a list of solarization plastic suppliers, publications, and references, (http://solar.uckac.edu/)

University of Idaho, Soil Solarization for Control of Soilborne Pest Problems (http://www.uiweb.uidaho.edu/ag/plantdisease/soilsol.htm)

8.7.5 Costs

Hasing et al. (2004) estimated strip solarization costs in lettuce to be around $304/acre, which included the cost of the plastic, and the labor for implementing and removing it. The increase in yield of the lettuce is thought to be likely to cover the increased costs compared to bare ground plots, however this benefit is commodity-specific. In general, plastic mulches, including installation and removal, run from $275 to $300 per acre (McCraw and Motes 2007) (**Table 8-11**).

For BMP comparative purposes, growers using synthetic mulch, either plastic or reflective, would be expected to see a cost increase of $285 to $316 per acre, with an average of $301 per acre, compared to an equivalent field without mulch (**Table 8-11**). These estimates assume all other production costs are held constant, which is likely to be an incorrect assumption if the use of mulch affects pesticide use, irrigation, or other production considerations. It is also possible that the mulch will affect yield, which would be reflected in changes in the net revenue.

Table 8-11. Cost per acre of synthetic mulches.
(Hasing et al. 2004, McCraw and Motes 2007)

	Representative	Minimum	Maximum
Plastic	299	285	311
Reflective	316	NA	NA
Together	301	285	316

NA = not available
Costs adjusted for inflation to reflect probable 2008 costs
(http://www.westegg.com/inflation/)

8.8 Variety Choice

8.8.1 Definition/Background

Pest control can be assisted in some cases by the choice of the variety of the crop. Certain varieties may have been classically bred for resistance to specific pests, or may exhibit asynchronous timing of vulnerable life cycle stages relative to the timing of the pest's impact. In addition, new genetically modified varieties can incorporate pesticides as an internal defense against pests, or increase the crop's pesticide tolerance, so that more effective pesticides can be used to control pests without damaging the commodity.

8.8.2 Effectiveness as a BMP

Preventive classical breeding: The effectiveness of using resistant varieties as a preventive BMP depends largely on whether the crop will still need to be sprayed for other pests. For example, the use of a lettuce variety resistant to the aphid *Nasonovia ribisnigri* still resulted in 39% of the lettuce being infested with aphid at the time of harvest, though with different species (Parker et al. 2002). On the other hand, the improved resistance of the almond kernel in the new Sweetheart variety of almond protects the nuts from a number of different pests, especially navel orangeworm (*Amyelois transitella*) and Indian meal moth (*Plodia interpunctella*) during post harvest storage (Gradziel et al. 2008).

Asynchronous timing: Walnuts are a good example of a commodity where asynchronous timing with a pest can allow variety selection to play an important role in pest impact. In general, walnut varieties that leaf and bloom earlier in the season are subject to rain-related diseases such as walnut blight (*Xanthomonas campestris* pv. *juglandis*) and are more likely to be infested by an early generation of the primary insect pest, codling moth (*Cydia pomonella*). Therefore, in areas with higher annual precipitation and/or heavy codling moth pressure, later leafing/blooming varieties can reduce the need for pesticides (Ramos 1998).

Genetically Modified: Genetically modified organism (GMO) crops have been rapidly gaining popularity in the US, with an increase of 33 million acres from 2005 to 2006. In 2006, there were eight predominant GMO crops grown in the US: herbicide resistant alfalfa, canola, corn, cotton, and soybean; virus resistant squash and papaya, and insect resistant corn, cotton, and sweet corn. Pesticide use was reduced by 110.06 million pounds that year, potentially in part due to the high use of GMOs (Johnson et al. 2007).

Many genetically modified insect resistant crops contain the microbial low risk pesticide *Bacillus thuringiensis* (Bt). If the internalized Bt is effective, higher risk sprays for certain pests could be reduced or eliminated. For example, Kumar and Kumar (2004) described a tomato variety that expressed a *cry1Ab* gene of Bt making the variety largely protected from the tomato fruit borer (*Helicoverpa armigera*), although complete control of the pest may require bio-control agents or limited pesticide use. Schahczenski and Adam (2006) summarized many studies, and concluded that changes in pesticide use as a result of planting transgenic crops is highly variable, depending on what non-transgenic crop it is compared to, as well as environmental and pest pressure conditions during the study. They concluded that of all the insecticidal transgenic crops, Bt cotton has shown the largest decrease in pesticide use.

In addition to insecticidal crops, there are also numerous herbicide tolerant genetically modified crops available. While these varieties do not prevent pesticide use, many are genetically modified to accommodate glyphosate, which is often considered to be a lower risk alternative than other herbicides. Canola, cotton, maize, and soybean comprise most of the transgenic crops with glyphosate resistance. In addition to glyphosate, transgenic crops have been created for use with glufosinate, dicamba (potential groundwater contaminant, FQPA Group 2), and bromoxynil (FQPA

Group 1), the latter two of which may have higher risks to human health and the environment (EPA 1997, CDPR 2009a). Schahczenski et al. (2006) reported that the change in pesticide use on herbicide tolerant crops compared to non-transgenic crops has been extremely variable, with various studies reporting either increases or decreases in use.

There can also be risks associated with the use of GMO crops, such as increased resistance of pests to Bt and/or decreased efficacy of natural predators due to decreased longevity (Gutierrez et al. 2006). In addition, five weed species in fields with glyphosate-tolerant transgenic crops have reportedly developed resistance, necessitating increased glyphosate use or use of other herbicides and/or weed management methods (Duke and Cerdeira 2007). Pink bollworm, a pest of cotton, seems to be an exception: no resistance alleles were detected in the DNA of pink bollworms despite ten years of exposure to Bt cotton (Tabashnik et al. 2006).

In summary, it is important to recognize that the use of GMO crops may result in decreased pesticide use, but is associated with many risks and/or perceived risks, such as the possibility of super weeds, allergenic effects, effects on non-target organisms and beneficial insects and predators, reduced crop genetic diversity, antibiotic resistance, food safety, and other unforeseen long term environmental effects (Schahczenski and Adam 2006). In addition, there are economic risks due to international marketing restrictions imposed by governments and consumers concerned about the potential environmental impacts of GMO crops.

8.8.3 Representative pesticides and commodities

UC IPM recommends a number of pest-resistant crop varieties and biological and cultural control options to control aphids in alfalfa and lettuce; aphids, armyworms, bollworms, loopers, mites, thrips, tobacco budworms, weevils, and whiteflies in cotton; and aphids and leafminers in tomatoes. If these pest-resistant crop varieties and biological and cultural control methods prove effective as preventive BMPs, applications of bifenthrin, chlorpyrifos, diazinon, and malathion could be significantly reduced, thus reducing the environmental impacts of these pesticides.

8.8.4 Helpful links and tools

Colorado State University offers a transgenic crop resource guide, which offers many links to resources on the technology and the issues concerning use of transgenic crops. (http://cls.casa.colostate.edu/TransgenicCrops/)

ATTRA offers a publication on transgenic crops (http://attra.ncat.org/attra-pub/PDF/geneticeng.pdf)

8.8.5 Costs

Transgenic crops will be used here as an example of variety cost differences, although it is likely to be a more extreme difference than cost differences between non-transgenic variety selections.

Many issues come into play when determining the profitability of transgenic crops. Seeds are often more costly, and include a technology fee per acre. Market price can vary, with some buyers willing to pay a premium for non-transgenic crops due to concern over consumer risk. Grain handlers may also reject transgenic crops, if their facility cannot sufficiently segregate the transgenic from the non-transgenic products in order to guarantee pure supplies. In addition, use of Bt crops legally requires the grower to establish refuges of a non-Bt version of the crop on a certain percentage of acreage in order to allow susceptible pests to survive and mate with pests that have become resistant to Bt, in order to delay the development of resistance by the pest population.

The imputed cost of such a refuge for cotton in California in 2002 was estimated at $10.66/acre, with a net gain in profit from using Bt cotton of $53.28/acre (Gianessi et al. 2002). Schahczenski and Adam (2006) reported that while costs are often lower for herbicide resistant crops compared to their non-transgenic counterparts, yields can be generally lower as well, resulting in overall profit being higher in non-transgenic crops. However, many insecticidal transgenic crops have shown increased yields compared to their conventional counterparts.

Table 8-12 compares the average conventional and transgenic costs and returns based on a survey of cotton growers in Georgia (Ward et al. 2001). Costs and price of cotton were adjusted to 2008 for comparative purposes.

For comparative BMP purposes, a grower using transgenic cotton would be expected to see a cost savings around $10 per acre compared to conventional cotton. In addition, net returns were around $78 per acre higher. Unlike many of the other BMP cost estimates, these values included the changes within the entire production system. Thus, production costs outside of the BMP were not held constant in this case.

Table 8-12. Comparing costs and returns for transgenic cotton and conventional cotton. Per-acre averages from growers surveyed in Georgia (Ward et al. 2001).

Inputs	**Transgenic**	**Conventional**
Fertilizer	67	70
Seed	29	9
Defoliant	21	23
Herbicide	37	37
Insecticide	28	39
Labor	12	16
Equipment	48	62
Scouting	9	7
Irrigation	34	31
Growth regulator	11	10
Interest	12	15
Total Variable Costs	**310**	**320**
Yield	986	874
Revenue @.0.61$/lb[a]	602	534
Returns above Variable Costs	**292**	**214**

Note: Costs adjusted for inflation to reflect probable 2008 costs (http://www.westegg.com/inflation/)
[a] (NASS 2009)

8.9 Preventive BMP Considerations

There are two important considerations that should be taken into account when deciding to implement preventive BMPs: the need to implement multiple complimentary preventive BMPs simultaneously for adequate pest control, and the species-specific limitations of individual preventive BMPs. First, it is often recommended that multiple, complementary preventive BMPs be implemented together in order to increase overall pest control effectiveness. Second, in contrast to most mitigative BMPs, preventive BMPs are usually more commodity-specific and pest-specific. Thus any reductions in pesticide use associated with preventive BMPs are likely to involve only one or a few pests. Hence, the grower may still need to employ pesticides if additional pests for which there are no known preventive BMPs are present.

To account for these considerations, the authors of this report attempted to measure the effectiveness of preventive BMPs in treating all of the likely pests a grower might encounter during the season. If preventive BMPs were available for all of the major pests, then, in theory, pesticide applications could be replaced by these lower risk practices. However, if there are many pests for which there are no available preventive BMPs, then pesticide applications, and potentially mitigative BMPs, will be necessary. In order to determine the number of pests that are currently controlled by representative pesticides that could instead be controlled using a preventive BMP, the following procedures were followed:

For each of the representative commodities, the major and minor pests were determined. Two charts were then created: the first chart showed which pests could potentially be treated by the five representative pesticides (based on inclusion of the commodity on pesticide labels). The second chart listed which preventive BMPs, if any, were recommended by UC IPM to control the pests included in the first chart, with the assumption that the BMP may be reasonably effective if UC IPM recommends it on their website. The next step was to determine how many pests could potentially be controlled by a preventive BMP rather than a representative pesticide. The following weighted average was employed:

$$\frac{\frac{(M_{BMP})}{M_{Total}} + (0.5)\frac{(m_{BMP})}{m_{Total}}}{1.5}$$

Where M_{Total} and m_{Total} are the total number of major and minor pests of a given representative commodity that can be treated with one or more representative pesticides, and M_{BMP} and m_{BMP} are the total numbers of those pests that can be treated with one or more preventive BMPs. Since minor pests are not always treated for by growers, they have been weighted at half that of the major pests.

Based on the weighted average calculations, the results indicate that 48% to 94% (average 74%) of the pests of the representative commodities were associated with at least one preventive BMP recommended for use by UC IPM (**Table 8-13**). Lettuce (48%) would be the commodity least likely to replace pesticides with preventive BMPs, while grapes and cotton had the highest likelihood (94% and 92% respectively). See **Table 8-13** for the full summary of findings.

The potential for preventive BMPs to effectively reduce the need for pesticide use was also calculated (**Table 8-14).** The same weighted average equation was used to assess the percentage of total pests of a commodity for which a preventive BMP could replace a representative pesticide, averaged over the representative commodities for each BMP.

Biological control had the broadest coverage, with the potential to replace representative pesticide use for around 41% of a representative commodity's total pests, averaged over all representative commodities. Early harvest, removal of pest habitat, fertilization/irrigation efficiency, resistant varieties, and spray trap crop/trench all were listed as potential pest controls for 20% or more of a commodity's total pests that could be controlled with a representative pesticide, averaged over the representative commodities (**Table 8-14**).

In contrast, dust reduction, mulches, timing of planting, barriers and crop rotation appeared to be more pest specific, only likely to replace a representative pesticide for less than 10% of a commodity's total pests, on average (**Table 8-14**).

Table 8-13. Preventive BMPs: potential to replace pesticides for representative commodities.

Commodity	M_{Total}	m_{Total}	M_{BMP}	m_{BMP}	**Weighted Average % pests treated by at least one BMP**
Alfalfa	5	4	4	3	78%
Almond	6	5	6	1	73%
Cotton	4	11	4	9	94%
Grapes	6	4	6	3	92%
Lettuce	11	1	8	0	48%
Tomato	2	8	1	8	67%
Walnut	4	5	2	5	67%

M_{Total} and m_{Total} are the total number of major and minor pests of a given representative commodity that can be treated with one or more representative pesticides, and M_{BMP} and m_{BMP} are the total number of those pests that can be treated with one or more preventive BMPs.

Table 8-14. Preventive BMPs: percent of pests controlled in representative commodities.

BMP	**Weighted Average: % pests treated by the given BMP**	**Minimum**	**Maximum**
Biological control	41	20	53
Removal pest habitat (Early Harvest)	32	22	43
Removal pest habitat (Sanitation)	22	11	48
Fertilization/ irrigation efficiency	22	11	42
Variety Choice (Resistant Varieties)	20	6	52
Trap Crop	20	20	20
Mulch (Solarization)	17	17	17
Cover crop	16	11	19
Irrigation (Flood)	15	8	19
Mulches/ solarization	14	11	17
Removal pest habitat (Flame/ hand-weed)	14	11	17
Removal pest habitat (Disk/till)	14	4	23
Inter-planting	13	13	13
Removal pest habitat (Cutting/ grazing/ mowing)	12	11	13
Mulches	8	8	8
Removal pest habitat (Timing of planting)	7	3	13
Barrier	5	4	6
Crop rotation	4	4	4

8.9.1 Representative commodities: pests and pest control options

Alfalfa: According to the UC IPM for Alfalfa Hay (UC IPM 1985a), alfalfa has five major pests, depending on the year and location. They include weevils (*Hypera postica, H. brunneipennis*), aphids (*Acyrthosiphon pisum, A. kondoi*), alfalfa caterpillars (*Colias eurytheme),* armyworms (*Spodoptera exigua, S. praefica*), and weeds. In addition there are around nine minor pests (four of which are treated with representative pesticides). Out of the five representative pesticides analyzed in this report, chlorpyrifos is registered to control the four major animal pests and two of the minor pests, while malathion controls three major and three minor pests, and bifenthrin controls two major and two minor pests (**Table 8-15**). Diuron controls multiple major and minor weed species. Diazinon is not registered for use in alfalfa. For major pests, biological controls, early harvests, timing of planting, planting density, fertilization/irrigation, cutting/grazing/mowing, interplanting, and resistant varieties are recommended. For the minor pests, biological controls, early harvest, disking, flooding, and removal of habitat are recommended (**Table 8-16**). Comparing the data presented in **Tables 8-15 and 8-16**, it appears that the use of representative pesticides could be replaced by a preventive BMP for all but one major pest and all but one minor pest.

Table 8-15. Pests of alfalfa treated with the representative pesticides.

Alfalfa Pest	Importance	Bifenthrin	Chlorpyrifos	Diuron	Malathion
alfalfa caterpillars	Major		x		
aphids	Major	x	x		x
armyworms	Major		x		x
weevils	Major	x	x		x
weeds	Both			x	
cutworms	minor		x		
leafhoppers	minor		x		x
lygus	minor	x			x
mites	minor	x			x

Other pests for which representative pesticides are not registered as controls:
Major: none; Minor: clover root curculio, sowbugs, thrips, treehoppers, webworms.

Table 8-16. Controlling alfalfa pests: preventive BMPs.
Rows in red signify a pest for which no preventive BMP was recommended by UC IPM.

Alfalfa Pest	**Biological control**	**Early harvest**[a]	**Disk / till**[a]	**Flood**[b]	**Sanitation**[a]	**Timing of planting**[a]	**Planting density**[c]	**Fertilization / irrigation efficiency**	**Cutting / grazing /**	**Inter-planting**	**Resistant Varieties**
alfalfa caterpillars	x	x									
aphids	x										x
armyworms	x	x									
weevils											
weeds						x	x	x	x	x	
cutworms			x	x	x						
leafhoppers		x									
lygus											
mites	x	x			x						

[a]Removal of Habitat
[b]Irrigation method
[c]Not covered in this report

Almond: According to the UC IPM for Almonds (UC IPM 2002), almonds have six major pests, depending on the year and location, including navel orangeworm (*Amyelois transitella*), ants (*Tetramorium caespitum, Solenopsis xyloni*), mites (*Tetranychus pacificus, T. urticae),* peach twig borers (*Anarsia lineatella*), scale (*Quadraspidiotus perniciosus*), and weeds, in addition to around sixteen minor pests (five of which can be treated with the representative pesticides). Out of the five representative pesticides analyzed in this report, chlorpyrifos is registered to control all five major animal pests and three minor pests, while bifenthrin controls four major and three minor pests, and diazinon controls one major pest (**Table 8-17**). Diuron controls multiple major and minor weed species. Malathion is not registered for use on almonds.

For major pests, biological control, early harvest, fertilization/irrigation efficacy, dust reduction, cutting/grazing/mowing, disking, cover crop, flaming, and removal of habitat are recommended. Only one of the five minor pests can be controlled by a preventive BMP: biological control for leaf-footed bugs (**Table 8-18**). Comparing the data in **Tables 8-17 and 8-18**, it appears that the use of representative pesticides could be replaced by a preventive BMP for all major pests but only one minor pest.

Table 8-17. Pests of almond treated with representative pesticides.

Almond Pest	Importance	Bifenthrin	Chlorpyrifos	Diazinon	Diuron
ants	Major	x	x		
mites	Major	x	x		
navel orangeworms	Major	x	x		
peach twig borers	Major	x	x		
scale	Major		x	x	
weeds	Both				x
american plum borers	minor		x		
leaffooted bugs	minor	x	x		
oblique banded leafrollers	minor	x			
peachtree borers	minor		x		
stinkbugs	minor	x			

Other pests for which representative pesticides are not registered as controls: Major: none; Minor: box elder bugs, carob moths, fruit tree leafrollers, lace bugs, leafhoppers, oriental fruit moths, pacific flatheaded borers, prune limb borers, shothole borers, tenlined june beetles, tent caterpillars

Table 8-18. Controlling almond pests: preventive BMPs.
Rows in red signify a pest for which no preventive BMP was recommended by UC IPM.

Almond Pest	Biological Control	Early Harvest[a]	Fertilization / Irrigation efficiency	Dust Reduction[b]	Cutting / grazing / mowing[a]	Disk / till[a]	Cover crop	Flame / hand-weed[a]	Sanitation[a]
ants		x							
mites	x		x	x					
navel orangeworm		x							x
peach twig borers	x								
scale	x								
weeds					x	x	x	x	
american plum borers									
leaffooted bugs	x								
oblique banded leafrollers									
peachtree borers									
stinkbugs									

[a]Removal of Habitat
[b]Not covered in this report

Cotton: According to the UC IPM for Cotton (UC IPM 1996), cotton has four major pests, depending on the year and location. They include bollworms (*Helicoverpa (Heliothis) zea, Pectinophora gossypiella*), tobacco budworms (*Heliothis virescens*), lygus (*Lygus hesperus),* and weevils (*Anthonomus grandis*). In addition there are around twenty-four minor pests of cotton. Chlorpyrifos and bifenthrin are registered to control all four major pests, as well as eleven and nine minor pests, respectively (**Table 8-19**). Malathion treats two major pests and seven minor pests. Diuron is predominantly used in defoliant products. Diazinon is not used on cotton.

For major pests, biological controls, early harvest, disking, flooding, fertilization/irrigation efficiency, spray trap crop/trench, resistant varieties, flaming, and removal of habitat were listed by UC IPM as potential pest controls (**Table 8-20**). For minor pests, biological control, early harvest, fertilization/irrigation efficiency, spray trap crop/trench, resistant varieties, timing of planting, and removal or pest habitat were listed (**Table 8-20**). Comparing the data in **Tables 8-19 and 8-20**, it appears that the use of representative pesticides could be replaced by a preventive BMP for all major pests and all but two minor pests.

Table 8-19. Pests of cotton treated with the representative pesticides.

Cotton Pest	Importance	Bifenthrin	Chlorpyrifos	Diuron	Malathion
bollworms	Major	x	x		
lygus	Major	x	x		x
tobacco budworms	Major	x	x		
weeds	Both			x	
aphids	minor	x	x		x
armyworms	minor	x	x		x
cotton leaf perforators	minor	x	x		x
cutworms	minor	x	x		
leafhoppers	minor	x			x
loopers	minor	x			
mites	minor	x	x		x
plant bugs	minor	x	x		
saltmarsh caterpillars	minor	x	x		
thrips	minor	x	x		x
whiteflies	minor	x	x		x

Other pests for which representative pesticides are not registered as controls:
Major: none; Minor: cotton square borers, cucumber beetles, darkling beetles, false cinch bug, field crickets, flea beetles, leafminers, leaftiers, omnivorous leafrollers, seedcorn maggots, webworms, whitelined sphinx, wireworms

Table 8-20. Controlling cotton pests: preventive BMPs.
Rows in red signify a pest for which no preventive BMP was recommended by UC IPM.

Cotton Pest	Biological Control	Early Harvest[a]	Disk/till[a]	Flood[b]	Fertilization/ Irrigation efficiency	Trap crop	Resistant Varieties	Timing of planting[a]	Flame/ hand-weed[a]	Sanitation[a]
bollworms	x	x		x	x		x			x
lygus						x				x
tobacco budworms	x	x			x		x			
Defoliant/weeds			x						x	
aphids	x				x		x	x		x
armyworms	x					x	x			
cotton leaf perforators	x	x								x
cutworms										x
leafhoppers	x									
loopers	x						x			
mites	x				x		x			
plant bugs										
saltmarsh caterpillars										
thrips							x			x
whiteflies		x			x		x			x

[a]Removal of Habitat
[b]Irrigation method

Grapes: According to UCANR Grape Pest Management (UCANR 1992), grapes have twelve major pests, depending on the year and location, including branch and twig borers (*Melaqus confertus*), cutworms (*Peridroma saucia, Amathes c-nigrum, Orthodes rufula*), grape bud beetles (*Glyptoscelis squamulata*), grape leaffolders (*Desmia funeralis*), grape phylloxera (*Daktulosphaira vitifoliae*), leafhoppers (*Erythroneura elegantula, E.variablilis*), mealybugs (*Pseudococcus maritimus*), mites (*Tetranychus pacificus, Eotetranychus willamettei*), ominvorous leafrollers (*Platynota stultana*), orange tortrix (*Argyrotaenia citrana*) , thrips (*Frankliniella occidentalis, Drepanothrips reuteri*), and western grapeleaf skeletonizers (*Harrisina brillians).* In addition there are around twenty-four minor pests. Six major pests and four minor pests can be controlled by the representative pesticides. Chlorpyrifos is registered to control two major and one minor pest, diazinon controls four major and one minor pest, and malathion controls three major and two minor pests (**Table 8-21**). Diuron controls major and minor weeds. Bifenthrin is not often used on grapes.

For major pests, biological controls, disking, fertilization/irrigation efficiency, flooding, control of another pest, cover crop, dust reduction, cutting/grazing/mowing, flaming, mulch/solarization, and removal of habitat were listed by UC IPM as potential pest controls (**Table 8-22**). For minor pests, biological controls, disking, fertilization/irrigation efficiency, flooding, control of another pest, and cover crop were listed as grape BMPs (**Table 8-**

22). Comparing the data in **Tables 8-21 and 8-22**, it appears that the use of representative pesticides could be replaced by a preventive BMP for all major pests and all but one minor pest.

Table 8-21. Pests of grapes treated with the representative pesticides.

Grape Pest	Importance	Chlorpyrifos	Diazinon	Diuron	Malathion
cutworms	Major	x			
grape leaffolders	Major		x		
leafhoppers	Major		x		x
mealybugs	Major	x	x		x
mites	Major		x		x
weeds	Both			x	
ants	minor	x			
aphids	minor		x		
scale	minor				x
vinegar flies	minor				x

Other pests for which representative pesticides are not registered as controls: Major: branch and twig borers, grape bud beetles, grape phylloxera, omnivorous leafrollers, orange tortix, thrips, western grapeleaf skeletonizers; Minor: armyworms, click beetles, darkling beetles, earwigs, false cinch bug, flea beetles, grasshoppers, hoplia beetles, little bear beetles, minor cicada, saltmarsh caterpillars, sphinx moths, termites, three-cornered alfalfa hoppers, weevils, western grape rootworms, whiteflies

Table 8-22. Controlling grape pests: preventive BMPs.
Rows in red signify a pest for which no preventive BMP was recommended by UC IPM.

Grape Pest	Biological Control	Disk / till[a]	Fertilization / Irrigation efficiency	Flood[b]	Control of another pest[c]	cover crop	Dust Reduction[c]	Cutting / grazing / mowing[a]	Flame / hand-weed[a]	Mulches / solarization	Sanitation[a]
cutworms	x			x							x
grape leaffolders	x										
leafhoppers	x										x
mealybugs					x						
mites	x		x				x				
weeds		x	x			x		x	x	x	
ants		x		x		x					
aphids (row in red)											
scale	x				x						
vinegar flies			x								

[a]Removal of Habitat
[b]Irrigation method
[c]Not covered in this report

Lettuce: According to UC IPM for Cole Crops and Lettuce (UC IPM 1985b), lettuce has thirteen major pests, depending on the year and location, including aphids (*Aulacorthum solani, Myzus persicae, Macrosiphum euphorbiae, Nasonovia ribis-nigri, Pemphigus bursarius*), armyworms (*Pseudaletia unipuncta*), corn earworms (*Heliothis zea*), cutworms (*Agrotis* *ipsilon, Peridroma saucia, Feltia subterranea*), flea beetles (*Systena blanda*), leafminers (*Liriomyza huidobrensis, L. trifolii, L. sativae*), loopers (*Trichoplusia ni, Autographa californica*), lygus (*Lygus hesperus*), saltmarsh caterpillars (*Estigmene acrea*), tobacco budworms (*Heliothis virescens*), darkling beetles (*Blapstinus spp., Caelus spp.),* whiteflies (*Bemisia argentifolii*) and weeds. In addition there are around ten minor pests of lettuce. Eleven of the thirteen major pests can be treated with representative pesticides, while only one of the ten minor pests can be treated. Bifenthrin is registered to control ten of the major pests, diazinon controls three major and one minor pest, and malathion controls two major pests (**Table 8-23**). Diuron and chlorpyrifos are not used on lettuce.

For major pests, biological controls, disking, fertilization/irrigation efficiency, barriers, resistant varieties, timing of planting, and removal of habitat were listed by UC IPM as potential pest controls (**Table 8-24**). No preventive BMPs were available for the minor pests. Comparing the data in **Tables 8-23 and 8-24**, it appears that the use of representative pesticides could be replaced by a preventive BMP for all but three major pests but none of the minor pests.

Table 8-23. Pests of lettuce treated with the representative pesticides.

Lettuce Pest	Importance	Bifenthrin	Diazinon	Malathion
aphids	Major	x	x	x
armyworms	Major	x		
corn earworms	Major	x		
cutworms	Major	x	x	
flea beetles	Major	x		
leafminers	Major		x	
loopers	Major	x		x
lygus	Major	x		
saltmarsh caterpillars	Major	x		
tobacco budworms	Major	x		
whiteflies	Major	x		
wireworms	minor		x	

Other pests for which representative pesticides are not registered as controls: Major: weeds, darkling beetles; Minor: cabbage maggots, diamondback moths, earwigs, false wireworms, garden symphylans, seedcorn maggots, slugs, snails, springtails

Table 8-24. Controlling lettuce pests: preventive BMPs.
Rows in red signify a pest for which no preventive BMP was recommended by UC IPM.

Lettuce Pest	Biological Control	Disk / till[a]	Fertilization / Irrigation efficiency	Barrier	Resistant Varieties	Timing of planting[a]	Sanitation[a]
aphids	x		x		x		x
armyworms		x					x
corn earworms	x						
cutworms							
flea beetles		x					x
leafminers	x						
loopers	x						
lygus							
saltmarsh caterpillars				x			
tobacco budworms							
whiteflies			x			x	x
wireworms							

[a]Removal of Habitat

Tomato: According to UC IPM for Tomatoes (UC IPM 1990), tomatoes have four major pests, depending on the year and location, including tomato fruitworms (*Helicoverpa (Heliothis) zea*), armyworms (*Spodoptera exigua*, *S. praefica*), tomato pinworms (*Keiferia lycopersicella*), and tobacco budworms (*Heliothis virescens*). In addition there are around seventeen minor pests. Two major pests and eight minor pests can be treated with the representative pesticides. Bifenthrin is registered to control two major and seven minor pests, diazinon controls one major and three minor pests, and malathion controls one minor pest (**Table 8-25**). Diuron and chlorpyrifos are not used on tomatoes.

For major pests, only biological controls are listed by UC IPM as potential pest controls. For minor pests, biological controls, barriers, crop rotation, disking, mulches, resistant varieties, and removal of pest habitat were listed as potential BMPs (**Table 8-26**). Comparing the data in **Tables 8-25 and 8-26**, it appears that the use of representative pesticides could be replaced by a preventive BMP for one out of two major pests and all minor pests.

Table 8-25. Pests of tomato treated by the representative pesticides.

Tomato Pest	Importance	Bifenthrin	Diazinon	Malathion
armyworms	Major	x	x	
tobacco budworms	Major	x		
aphids	minor	x	x	x
cutworms	minor	x	x	
flea beetles	minor	x		
leafminers	minor		x	
loopers	minor	x		
saltmarsh caterpillars	minor	x		
stinkbugs	minor	x		
whiteflies	minor	x		

Other pests for which representative pesticides are not registered as controls: Major: weeds, tomato fruitworms, tomato pinworms; Minor: darkling beetles, garden symphlans, mites, potato tuberworms, seedcorn maggots, thrips, tobacco hornworms, tomato hornworms, wireworms

Table 8-26. Controlling tomato pests: preventive BMPs.
Rows in red signify a pest for which no preventive BMP was recommended by UC IPM.

Tomato Pest	Biological Control	Barrier	Crop rotation	Disk/till[a]	Mulches	Resistant Varieties	Sanitation[a]
armyworms	x						
tobacco budworms							
aphids	x				x	x	
cutworms				x			x
flea beetles			x				
leafminers	x					x	x
loopers	x						
saltmarsh caterpillars		x					
stinkbugs	x						x
whiteflies					x		x

[a]Removal of Habitat

Walnut: According to UC IPM for Walnuts (UC IPM 2003), walnuts have four major pests, depending on the year and location, including codling moth (*Cydia pomonella*), navel orangeworm (*Amyelois transitella*), walnut husk fly (*Rhagoletis completa*), and weeds. In addition there are around eleven minor pests. All four major pests and five minor pests can be treated by the representative pesticides. Bifenthrin is registered to control all three of the major animal pests and four minor pests, chlorpyrifos controls two major and three minor pests, diazinon controls one major and three minor pests, and malathion controls one major and two minor pests (**Table 8-27**). Diuron controls major and minor weeds.

For major pests, early harvest disking, fertilization/irrigation efficiency, control of another pest, cover crop, solarization, flaming, and removal of pest habitat were listed by UC IPM as potential pest controls. For minor pests, biological controls, early harvest, disking, fertilization/irrigation efficiency, and dust reduction were listed as possible controls (**Table 8-28**). Comparing the data in **Tables 8-27 and 8-28**, it appears that the use of representative pesticides could be replaced by a preventive BMP for two out of the four major pests and all minor pests.

Table 8-27. Pests of walnuts treated with the representative pesticides.

Walnut Pest	Importance	Bifenthrin	Chlorpyrifos	Diazinon	Diuron	Malathion
codling moths	Major	x	x	x		
navel orangeworms	Major	x				
walnut husk flies	Major	x	x			x
weeds	Both				x	
ants	minor	x	x			
aphids	minor	x	x	x		x
mites	minor	x		x		x
plant bugs	minor	x				
scale	minor		x	x		

Other pests for which representative pesticides are not registered as controls: Major: none; Minor: earwigs, leafminers, redhumped caterpillars, thrips, webworms, western tussock moths

Table 8-28. Controlling walnut pests: preventive BMPs.
Rows in red signify a pest for which no preventive BMP was recommended by UC IPM.

Walnut Pest	Biological Control	Early Harvest[a]	Disk/till[a]	Fertilization/ Irrigation efficiency	Dust Reduction[b]	Control of another pest[b]	Cover crop	Mulch/Solarization	Flame/ hand-weed[a]	Sanitation[a]
codling moths										
navel orangeworms		x				x				x
walnut husk flies										
weeds			x	x			x	x	x	
ants		x								
aphids	x									
mites	x			x	x					
plant bugs			x							
scale	x									

[a]Removal of Habitat
[b]Not covered in this report

9 Effectiveness of select BMPs with respect to soil infiltration, groundwater, air quality, and terrestrial organisms

The primary focus of this report is to identify effective BMPs for preventing or mitigating off-site movement of pesticides and other contaminants from agricultural lands into surface waters of California's Central Valley. However, it is also important to identify BMPs that address other environmental concerns such as leaching, groundwater contamination, air quality, and terrestrial organisms.

9.1 Leaching and Groundwater Contamination

Some pesticides and other agricultural products have been found in groundwater, which poses health concerns when people access that contaminated groundwater with wells for domestic and/or agricultural uses. Around 70 pesticides used in the Central Valley have been identified as having the potential to pollute groundwater, as listed on the California Department of Pesticide Regulation (CDPR) 6800 Groundwater Protection List (CDPR 2007a). These official pollutant listings reflect many studies which have either documented pesticide concentrations at levels considered toxic or above recommended thresholds for both surface and groundwater in California (Domagalski et al.1997, Bennett et al. 1998, Troiano et al. 2001, Weston et al. 2004), or predicted toxic concentrations through fate and transport modeling studies, such as those conducted by the authors of this report (Liu et al. 2008, Luo et al. 2008, Zhang et al. 2008a, b, Ficklin et al. 2009, Luo and Zhang 2009a, b, c, Zhang et al. 2010).

Groundwater can also be impacted from pesticide leaching through soils, especially when applied just before a major precipitation or irrigation event. Kazemi et al. (2009) found that aldicarb and carbofuran moved deeper into a dry soil profile that was irrigated compared to a previously wet soil profile that was irrigated, due to higher pore water velocity in the dry soil. In addition to deeper transport, there was an increased persistence of the pesticides.

9.1.1 Representative Pesticides

- Diazinon

Diazinon is listed in the CDPR 6800 groundwater list as a potential pollutant (CDPR 2007a).

- Diuron

Diuron has been found in California groundwater in the two to three parts per billion (ppb) range (EXTOXNET, 1996). It is included in the California

Department of Pesticide Regulation (CDPR) 6800 Groundwater Protection list as a chemical with the potential to pollute groundwater (EXTOXNET 1996, EPA 2006a, CDPR 2007a, FOOTPRINT 2009).

9.1.2 BMPs

Conservation tillage, application timing, irrigation efficiency, and the use of cover crops were the four BMPs associated with mitigation of pesticide leaching to groundwater that were analyzed in this report. All four lacked sufficient quantitative data regarding the percentage reduction in leaching. While conservation tillage can increase organic matter and thus increase the potential for pesticide adsorption, it also improves soil infiltration, which can result in pesticide leaching (Seelig 1996). Many studies have verified higher leaching of pesticides in conservation tillage fields as compared to conventional tillage practices (Hall et al. 1989, Clay et al. 1991, Hall and Mumma 1994, Isensee and Sadeghi 1994, 1995). Hall et al. (1989) found that no till practices increased leaching of various herbicides to a soil depth of 122 cm from 0.3% to 5.6%. Isensee and Sadeghi (1994) found that short term levels of herbicides in groundwater were 2 to 50 times greater under no till than conventional tilled plots. It is therefore possible that conservation tillage may exchange surface water quality impacts for groundwater quality impacts. The effectiveness of application timing and irrigation efficiency as groundwater leaching BMPs was also uncertain, with quantitative study results unavailable or inconclusive. Both irrigation efficiency and application timing appeared promising, however.

9.2 Air Quality: Drift and VOCs

Pest management practices have also been shown to impact air quality. Over 70% of California's counties fail to meet the Clean Air Act National Ambient Air Quality Standard for Ground Level Ozone. Ozone is formed from reactions between nitrogen oxides and volatile organic compounds (VOCs). VOCs are emitted by many commonly used agricultural pesticide formulations, such as fumigants and emulsifiable concentrates (EPA 1993). Ozone, which contributes to smog, is linked to a number of health problems such as chest pain, coughing, throat irritation, and congestion, and can worsen bronchitis, emphysema, and asthma (CDPR 2007c).

In addition to issues related to VOCs, 43 pesticides are included in the CDPR 6860 Toxic Air Contaminants List, due to exceedances of thresholds for adverse health effects during monitoring studies after agricultural applications (CDPR 2007b). Air contamination can occur from drift and volatilization of the pesticide during application. In a study on dormant season diazinon application to peaches in the Central Valley, Glotfelty et al. (1990) concluded that most of the pesticide was lost through volatilization over time, compared to drift. The rate of volatilization of pesticides applied directly to soil is largely affected by the soil moisture content, with less vapor losses from dry soils than from those at field capacity moisture levels. Pesticides that adsorb to the dry soil particles can be displaced by water when moisture is added, thus allowing evaporation into the atmosphere (EPA 1993).

9.2.1 The five representative pesticides

Application timing could reduce the air quality impacts of bifenthrin, chlorpyrifos, and malathion, which are all volatile.

- **Diuron**

Diuron active ingredient is not listed in the 6860 air contaminant list (CDPR 2007b), and is non-volatile (K_h = 2.00 x 10^{-6} Pa m^3 mol^{-1} at 25 ^oC) (FOOTPRINT 2009). However in 2006, diuron products containing VOC, summed over five non-attainment areas of California, produced a total of 4201 lbs of VOC emissions. It thus ranked 123rd out of the 503 pesticides for which CDPR calculated the pounds of VOC emissions produced, contributing 0.04% of the total VOC emissions produced that year from pesticides (CDPR 2009d).

- **Bifenthrin**

Bifenthrin has not been listed as an air contaminant on the CDPR 6860 list, and it has low volatility (K_h = 7.74 X 10^{-5} Pa m^3 mol^{-1} at 25^oC) (FOOTPRINT 2009). However, in 2006, bifenthrin products produced a total of 57,155 lbs of VOC emissions, summed over the five non-attainment areas of California. It thus ranked 31st out of the 503 pesticides for which CDPR calculated the pounds of VOC emissions produced, contributing 0.50% of the total VOC emissions produced that year from pesticides. It was in the top ten primary active ingredients contributing to 2007 VOC emissions for the South Coast non-attainment area (CDPR 2009d).

- **Chlorpyrifos**

Chlorpyrifos is not included on the CDPR 6860 air contaminant list, and it has moderate volatility (K_h = 0.478 Pa m^3 mol^{-1} at 25^oC) (FOOTPRINT 2009). However, in 2006, chlorpyrifos products produced a total of 1,531,458 lbs of VOC emissions, summed over five non-attainment areas of California. It thus ranked first out of the 503 pesticides for which CDPR calculated the pounds of VOC emissions produced, contributing 13.27% of the total VOC emissions produced that year from pesticides. It was among the top ten primary active ingredients contributing to 2007 VOC emissions in the Sacramento Metropolitan, Ventura and San Joaquin Valley non-attainment areas (CDPR 2009d).

- **Diazinon**

Diazinon is not included on the CDPR 6860 air contaminant list, and has low volatility (K_h = 6.09 X 10^{-2} Pa m^3 mol^{-1} at 25^oC) (FOOTPRINT 2009).

However, in 2006 diazinon products produced a total of 21,585 lbs of VOC emissions, summed over five non-attainment areas of California. It thus ranked 58th out of the 503 pesticides for which CDPR calculated the pounds of VOC emissions produced, contributing 0.19% of the total VOC emissions produced that year from pesticides (CDPR 2009d).

- ### Malathion

Malathion is not included on the CDPR 6860 air contaminant list, and has a low volatility (K_h = 1.00 X 10^{-3} Pa m^3 mol^{-1} at 25^oC) (FOOTPRINT 2009). However, in 2006, malathion products produced a total of 26,458 lbs of VOC emissions, summed over five non-attainment areas of California. It thus ranked 51st out of the 503 pesticides for which CDPR calculated the pounds of VOC emissions produced, contributing 0.23% of the total pesticide VOC emissions produced that year (CDPR 2009d).

9.2.2 Effective BMPs

Drift reducing sprayers/shields and windbreaks were the BMPs found to effectively decrease the impact of pesticide drift on air quality. Pesticide formulation changes were analyzed as a BMP to reduce volatile organic compounds (VOCs). On average, windbreaks appeared to reduce drift (77% reduction) more than sprayers and shields (50% reduction). However, the variation in the data of windbreaks was much higher than that of sprayers and shields, with the lower range only slightly above that of the estimation for sprayers and shields. Both BMPs were associated with cost increases, with sprayers and shields averaging an increase of $327 per acre and windbreaks averaging an increase of $796 per acre.

Pesticide formulation choice appeared to be fairly effective as a BMP for reducing VOCs, averaging an 81% reduction upon switching to formulations with lower VOC emissions. In addition, the change in cost was relatively low, ranging from a savings of $15 per acre to a cost increase of $40 per acre.

9.2.3 VOC Potential

Potential volatile organic compound (VOC) emissions are calculated by multiplying the pounds of applied pesticide product by its emission potential (EP), which was determined by thermogravimetric analysis. The EP of a pesticide is the fraction of the product that is thought to contribute to atmospheric VOCs. Fumigants and pesticides in emulsifiable concentrate (EC) formulations contribute a high proportion of all pesticide-emitted VOCs. CDPR maintains a VOC emissions database from pesticide applications made between May 1st and October 31st (the peak ozone season in California), in five of California's ozone standard non-attainment areas (Sacramento Metropolitan, San Joaquin Valley, Southeast Desert, Ventura, and the South Coast) (CDPR 2009d).

Table 9-1 shows the effect of formulation on VOC emissions. For all of the 5 representative pesticides, the aqueous formulations produced larger amounts of VOCs compared to the dry formulations, based on the total pounds of each product used in California in 2007. However, for dry formulations with high recommended use rates, switching from an emulsifiable concentrate formulation to a dry formulation may actually increase VOCs, as seen with malathion. While the EP of the dry formulation, malathion 5 dust (1.53%), is much lower than the EP of the aqueous formulation, malathion 8EC (19.21%), the pounds of product recommended for use (50 lbs per acre) is sufficiently higher than that of the EC (3 lbs per acre), resulting in a 37% increase in VOCs per application. For most other pesticides, though, switching from an aqueous formulation to a dry one will lower the amount of VOCs, as seen in **Table 9-1** where VOCs decreased from 71% to 92%.

Table 9-1. VOC emissions: various formulations of the five representative pesticides. (CDPR 2009c, d)

Active Ingredient	Formula	Product	EP (%)[a]	Pounds Product used in CA, 2007[b]	Pounds VOCs in 2007	lbs per acre[c]	VOCs per acre	% change VOC with dry formulation
Bifenthrin	Dry	Brigade Wsb	1.85	155,559	2,878	1.06	2	-84%
Bifenthrin	Aqueous	Capture 2EC	37.1	24,291	9,012	0.34	12	
Chlorpyrifos	Dry	Lorsban 15G	5.33	411,087	21,911	8.39	45	-71%
Chlorpyrifos	Aqueous	Lorsban 4E	39.15	2,373,623	929,273	3.98	156	
Diazinon	Dry	Diazinon 50 WP	4.52	91,233	4,124	1.21	5	-92%
Diazinon	Aqueous	Diazinon Ag500	41.7	389,572	162,452	1.74	73	
Malathion	Dry	Malathion 5	1.53	147,590	2,258	50.35	77	+37%
Malathion	Aqueous	Malathion 8EC	19.21	257,756	49,515	2.93	56	
Diuron	Dry	Karmex Df	2.73	65,429	1,786	1.85	5	-88%
Diuron	Aqueous	Diuron 4L	12.57	77,263	9,712	3.45	43	

[a,b] (CDPR 2009c, d), [c]average pounds of product used per acre treated as reported for all of California in the PUR database, 2007

9.3 Risks to Humans, other Terrestrial Mammals, and Birds

9.3.1 Farm Worker and Bystander Exposure

Many studies have documented links between direct pesticide exposure and health problems in California. Clary and Ritz (2003) reported increased pancreatic cancer mortality in areas of high exposure to organochlorines. Mills (1998) found correlations between pesticide exposure and cancer in Hispanic and black men, representing segments of the population that have traditionally been employed as farm workers and are therefore more vulnerable to exposure. Ritz and Yu (2000) and Ritz and Costello (2006)suggested that pesticide use in the Central Valley may play a role in Parkinson's disease, and Roberts et al. (2007) associated pesticide exposure with autism spectrum disorders among Central Valley children. As a result, the Food Quality Protection Act (FQPA) has restricted or eliminated use of many pesticides, often requiring buffers between sites of pesticide application and residential areas and/or natural resources. High demand for housing has caused many new residential developments to encroach upon regions once traditionally agricultural, thus further fueling the problems of pesticide exposure.

9.3.2 Mammals: toxicity of the five representative pesticides

- Diuron

Diuron has a low to moderate acute toxicity to mammals, with a rat oral LD_{50} ranging from 437 to 3,750 mg kg^{-1}. The NOELs reported in an EPA integrated risk information system assessment for mammals ranged from 25 to 125 mg kg^{-1}, with low reported confidence in the results. Diuron has been listed as a Group 2 chemical under the Food Quality Protection Act (FQPA), signifying that it is a possible human carcinogen, though of less priority for re-registration evaluation than the risk- and hazard-based priority chemicals in Group 1 (EXTOXNET 1996, EPA 1997, FOOTPRINT 2009).

- Bifenthrin

Bifenthrin has a high acute toxicity to mammals, with a rat oral LD_{50} ranging from 54 to 70 mg kg^{-1}, and a NOEL of 5 mg kg^{-1}. It is listed as a Group 2 pesticide on the FQPA re-registration list (EPA 1997).

- Chlorpyrifos

Chlorpyrifos has a high acute toxicity to mammals, with a rat oral LD_{50} ranging from 66 to 270 mg kg^{-1}, and a NOEL of 1 mg kg^{-1}. It is listed as a Group 1 pesticide in the FQPA re-registration list, as a risk- and hazard-based priority (EPA 1997).

- Diazinon

Diazinon has moderate to high toxicity to mammals, with a rat oral LD_{50} of 1,139 mg kg^{-1} and a NOEL of 5 mg kg^{-1} (FOOTPRINT 2009). It is listed as a Group 1 pesticide in the FQPA re-registration list, as a risk- and hazard-based priority (EPA 1997).

- Malathion

Malathion has low to moderate acute toxicity to mammals, with a rat oral LD_{50} of 1,000 to 10,000 mg kg^{-1} and a higher chronic toxicity with a NOEL of

34.5 mg kg^{-1} (FOOTPRINT 2009). It is listed as a Group 1 pesticide in the FQPA re-registration list, as a risk- and hazard-based priority (EPA 1997).

9.3.3 Birds: toxicity of the five representative pesticides

- Diuron

Diuron is slight to moderately toxic to birds, with an LD_{50} of 1104 mg kg^{-1}. LC_{50}s range from 1,730 to greater than 5,000 mg kg^{-1} (EXTOXNET 1996, FOOTPRINT 2009).

- Bifenthrin

Bifenthrin has low to moderate toxicity to birds, with an LD_{50} of 569 to 2,150 mg kg^{-1} for birds in general. In addition, EXTOXNET reports bioaccumulation concerns for birds (EXTOXNET 1996, FOOTPRINT 2009).

- Chlorpyrifos

Chlorpyrifos is also highly toxic to birds, with an LD_{50} of 8.41 to 112 mg kg^{-1} for birds in general (EXTOXNET 1996, FOOTPRINT 2009).

- Diazinon

Diazinon is considered highly toxic to birds, with an LD_{50} from 2.5 to 40.8 mg kg^{-1} for birds in general, and 8 mg kg^{-1} for mallards (EXTOXNET 1996, FOOTPRINT 2009).

- Malathion

Malathion is moderately toxic to birds, with an LD_{50} from 100 to 3,000 mg kg^{-1} for birds in general (EXTOXNET 1996, FOOTPRINT 2009).

9.3.4 Application timing: effects on birds and bees

While pesticides can negatively impact many types of aquatic and terrestrial wildlife, there is some evidence that application timing can reduce these impacts to bees and certain birds species.

Some bird species are only associated with agricultural areas in certain regions and certain times of the year. The online database listed in the links and tools section below can assist growers with learning which bird species are likely to be found in their fields and when. Consideration can then be given to using products known to be less harmful to those birds during those time periods.

The impact of pesticides on bees can be largely reduced through timing considerations as well. Pesticides known to be toxic to bees and other pollinators should be avoided during bloom times of the crop, any cover crops, or any adjacent vegetation, to the extent possible. Growers should also refrain from applying toxic pesticides if low temperatures are forecast or dew is expected following the application, as these conditions can double the persistence of the pesticide residue. Any insecticides with a residual hazard to bees four to eight hours following application should be applied between late evening and midnight, to avoid peak foraging time and activity (Riedl et al. 2006).

- Links and tools

Birds in Agricultural Areas database put out by the American Bird Conservatory (http://www.abcbirds.org/abcprograms/policy/pesticides/biaa/index.html)

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11 Appendix

Papers published on BMP literature reviews.