Agricultural Systems 103 (2010) 294–306

Contents lists available at ScienceDirect

Agricultural Systems

journal homepage: www.elsevier.com/locate/agsy

Quantifying economic and environmental tradeoffs of walnut arthropod pest management

Kimberly P. Steinmann[a], Minghua Zhang[a,*], Joseph A. Grant[b], Carolyn Pickel[c], Rachael E. Goodhue[d], Karen Klonsky[d]

[a] Department of Land Air and Water Resources, University of California, 1 Shields Avenue, Davis, CA 95616, USA
[b] University of California, Cooperative Extension San Joaquin County, 420 South Wilson Way, Stockton, CA 95205, USA
[c] University of California, Cooperative Extension Sutter-Yuba Counties, Sutter County Agricultural Building, 142 Garden Highway, Suite A, Yuba City, CA 95991-5512, USA
[d] Department of Agricultural and Resource Economics, University of California, 1 Shields Avenue, Davis, CA, 95616, USA

ARTICLE INFO

Article history:
Received 27 March 2009
Received in revised form 1 February 2010
Accepted 23 February 2010
Available online 17 March 2010

Keywords:
Economic
Water quality
Tradeoff
Walnut
Pesticide

ABSTRACT

Many arthropod pesticides used by California walnut growers have been linked to water quality impairment. However lower risk alternatives are often associated with higher costs. The purpose of this paper was to: (1) identify currently practiced pest management strategies with probable high water quality impact, (2) quantify the importance of factors which affect economic tradeoffs associated with reducing water quality impact, and (3) identify pest management strategies that could potentially lower water quality impact with less economic consequence. An integrated analysis using environmental, economic and pesticide use data revealed that 96% of the pest management strategies analyzed were candidates for reducing the impact on water quality. Replacement of current pesticides by alternative pest controls lowered probable impact, but resulted in an economic tradeoff in the form of higher costs for the majority of growers. If biological control could eliminate the need for miticides and aphicides, this tradeoff could be replaced by savings for nearly half of the sample analyzed. This cost savings would most likely be realized by growers who currently have low numbers of pests that are not candidates for biological control, and relatively high use of organophosphates and miticides. The results indicated that if these pest management strategies had been replaced by alternative strategies and biological control, then total organophosphate, pyrethroid, and miticide active ingredient use would have been reduced by an average of 5 kg/hectare per year, while simultaneously lowering the grower's pest management costs by an average of $128/hectare, thus contributing to both economic and environmental long-run sustainability.

1. Introduction

In 2006, California led the United States in agricultural cash farm receipts, totaling $31.4 billion, which represents 13.1% of the national total. Six of the top 10 California counties were in the San Joaquin Valley, an area considered to be one of the most agriculturally productive regions in the world. Fruit and nut crops, many of which are grown exclusively in California, contributed 33% of the state's total receipts (CDFA, 2007). This high level of agricultural productivity has come at a cost, however, with 46 out of 100 impaired waterbodies in the Central Valley resulting from pesticide use (EPA, 2006). This study examines these issues through an analysis of the environmental and economic consequences that would occur if walnut growers were to alter their pest management strategies to lower surface water quality impacts generated by pesticide runoff in the San Joaquin Valley.

Currently, many walnut growers employ conventional, broad spectrum pesticides. While they are cost effective in controlling multiple pests at once, they also pose substantial risks to aquatic ecosystems and water quality through unintended harm to non-pest species. While pesticide use on walnuts during months of high precipitation (November–February) is relatively low, it can be high during the summer months when irrigation runoff facilitates off-site movement of pesticides to waterbodies (Schwankl et al., 2007; CDPR, 2008; CIMIS, 2008). Many newer pesticides have been developed that are believed to have a lower negative impact to water quality than the conventional products. Besides having generally lower toxicity, these soft alternatives differ from their broad spectrum counterparts in that they are more selective, acting against only narrow ranges of species. Thus, if an alternative product enters a waterbody via runoff, the combination of lower

* Corresponding author. Tel.: +1 530 752 4953; fax: +1 530 752 5262.
E-mail addresses: kpsteinmann@ucdavis.edu (K.P. Steinmann), mhzhang@ucdavis.edu (M. Zhang), jagrant@ucdavis.edu (J.A. Grant), cxpickel@ucdavis.edu (C. Pickel), goodhue@primal.ucdavis.edu (R.E. Goodhue), klonsky@primal.ucdavis.edu (K. Klonsky).

0308-521X/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.agsy.2010.02.002

toxicity and higher selectivity reduces the potential for harm to non-pest species compared with conventional products.

Growers have been slow to adopt these alternative products, however, due to perceived drawbacks such as higher material costs, more applications per season, and/or increased monitoring requirements. These costs may be offset by potential savings associated with secondary pest control if biological control by natural enemies is sufficient to maintain secondary pest populations below economically damaging levels. Many studies have documented higher populations of natural enemies of pests in crops treated with selective controls compared to those treated with broad spectrum pesticides (Zalom et al., 2001; Agnello et al., 2003; Prischmann et al., 2005). Therefore, a grower using alternative selective pest controls will likely have a larger population of natural enemies, and thus a greater potential for effective biological control that can replace the need for certain pesticides and lower costs. Depending on the grower's current practices, the potential savings could make an alternative pest management system economically competitive with conventional systems.

In order for walnut growers to achieve long-run agro-ecological sustainability, pest management must be based on practices that are both economically viable and environmentally sound. Detailed information is therefore needed on both environmental impact and economic considerations associated with production practices. This study attempts to identify the specific tradeoffs between economic and surface water quality impacts associated with different pest management strategies (PSs) in California walnut production systems. The objectives of this paper are as follows: (1) to identify currently practiced PSs with probable high negative water quality impact, (2) to measure potential tradeoffs in the form of increased pest management costs if the grower were to lower impact to water quality through solely using alternative products, and (3) to quantify the relative importance of different factors affecting these tradeoffs, in order to identify the current PSs that could potentially lower impact with the least economic consequence, and thus meet the goals of sustainable agriculture.

2. Materials and methods

2.1. Definitions

In this study, a PS was defined as all insect and mite pest control products used during a year by a grower. A tradeoff was defined as the dollar per hectare amount that the cost of the PS would increase if the grower adopted an alternative PS equivalent in pest control efficacy to their current practices in order to lower water quality impacts to an acceptable level. If the cost decreased or remained the same, both the environment and the grower benefited, and there was not a tradeoff upon adoption of the alternative strategy. The more complex notions of water quality impact measurement, acceptable impact level, and alternative strategies are explained in detail in later sections.

2.2. Commodity, study area and sample

Walnuts were chosen for analysis due to their economic importance in California, their high reliance on broad spectrum conventional pesticides, and the strong potential for risk reduction via the emergence of many newer alternative products (EPA, 1997, 2006; CDFA, 2007). Multiple years and counties were included in the analysis to reflect the broad range of spatial and temporal variation of currently practiced PSs. The study area included the three contiguous counties of San Joaquin, Stanislaus, and Merced, which represent approximately 1/3 of total walnut production in California (CDFA, 2007; CASS, 2008). Data were analyzed over the 5 year time span from 2002 through 2006.

The PS, rather than the grower, was the experimental unit of this analysis. For a PS to be included in the sample, it needed to meet the following two criteria. First, given the economic importance of the primary walnut pest, codling moth (*Cydia pomonella*), only PSs that indicated treatment for codling moth, either alone or with other pests, were chosen for analysis. Second, PSs using solely alternative pest controls were excluded because they represented only about 1% of the potential PSs identified. Thus, all PSs in the sample included conventional products, either alone or in conjunction with alternatives, to treat pests.

Each grower in the study area could contribute from zero to five PSs to the analysis, depending on whether the grower employed a PS meeting the above two criteria in any of the 5 years analyzed. Furthermore, the PSs contributed by a grower could vary from year to year or remain the same, depending on the particular pesticides and use rates employed by the grower during the year. The resulting sample of all three counties over 5 year included 2531 PSs for analysis, representing the practices of 891 growers on approximately 14,164 hectares of walnuts.

2.3. Data sources

2.3.1. Environmental data

Environmental data consisted of environmental indices that are available online for over 300 pesticides as part of the Environmental Impact Quotient (EIQ) model, created by Kovach et al. (1992, 2007). This model has been used by a wide range of international authors and policy makers on a diverse set of crops and locations (Edwards-Jones and Howells, 2001; Gallivan et al., 2001; Smith et al., 2002; Bues et al., 2004; Brimner et al., 2005; Brookes and Barfoot, 2005; Badenes-Perez and Shelton, 2006; Cross and Edwards-Jones, 2006; Kleter et al., 2007). While the EIQ model includes indices for many different environmental mediums, only the surface water quality index, represented by the impact of pesticides on fish, was used in this study. While aquatic systems are comprised of many varied species, fish are generally thought to be good indicators of overall toxicity, with fish toxicity values often correlating well with those of aquatic invertebrates (Kenaga, 1978; Maki, 1979). The water quality index values for a total of 33 different dominant active ingredients of the pesticide products used in the PSs analyzed by this study were downloaded.

The unit-less water quality indices were calculated by Kovach et al. (1992) for each active ingredient as the product of a 96 h LC_{50} rank for fish and a surface loss potential (runoff) rank. Kovach et al. (1992) assigned the LC_{50} rank a value of 1 if the LC_{50} was greater than 10 μl/l or mg/l, a value of 3 if the LC_{50} was between 1 and 10 μl/l or mg/l, and a value of 5 if the LC_{50} was less than 1 μl/l or mg/l. Similarly, the runoff rank was assigned values of 1, 3, or 5, based on whether the runoff potential was small, medium, or large, respectively, according to the Groundwater Loading of Agricultural Management Systems (GLEAMS).

These water quality indices were therefore solely based on active ingredient toxicity and exposure characteristics. They did not take into account the effects of environmental characteristics such as slope, soil, application timing relative to precipitation or irrigation, proximity to waterbodies, and/or the use of best management practices, all of which can influence the probability of a pesticide reaching a waterbody. Furthermore, the indices did not account for other modes of offsite transport to waterbodies, such as airborne drift. The exclusion of environmental characteristics from the model ignores their possible mitigating effects on offsite movement of pesticide from a field to a waterbody, which may lead to over-estimation of impacts. In contrast, the absence of modes of transport in the model other than runoff can lead to an under-estimation of impact if drift is significant.

The Kovach et al. (1992) model did not evaluate puffer pheromone ((E,E)-8,10-Dodecadien-1-ol) mating disruption, which is an important alternative codling moth control analyzed in this paper. Given that pheromone volatizes rapidly (Vapor pressure (25 °C): 69, Henry's Law Constant (20 °C): 2.03×10^{-4}), leaving little residue, and the LC_{50} of the active ingredient in the related product, Isomate C, is greater than 120 mg/l, scoring a rank of 1, a value of 1 was used as the water quality index for pheromone (PMRA, 1994; OECD, 2002; FOOTPRINT, 2008).

2.3.2. Pesticide use and economic data

Pesticide use data included product choice, application date, use amount, hectares treated, and total hectares planted, as reported by walnut growers to the Pesticide Use Reports (PUR) database maintained by the California Department of Pesticide Regulation (CDPR, 2008). Since 1990, California regulations have required growers to report all pesticide use on fields, resulting in a publicly accessible database which can be used for analysis of total pesticide use at the grower and field level. By using actual grower-reported data, the results were expected to reflect real-time grower experiences. To ensure data quality, CDPR implements an extensive procedure for dealing with errors and outliers in the PUR data, which was supplemented in this study by comparing PUR data to product label rates (Wilhoit, 2002). PSs with suspected errors or outliers were eliminated from the analysis. Economic data consisted of pesticide prices from several sources and a standardized custom applicator cost. These were combined with PUR-reported pesticide use amounts and hectares treated to determine each growers' total pest management costs per hectare.

In addition to the pesticides reported by walnut growers to the PUR database, alternative pest controls and application rates were included in hypothetical alternative pest management systems (APSs), for comparisons of environmental and economic impact. These alternative pest controls were chosen based on a review of field and laboratory trials, as well as opinions from University of California farm advisors and professors with expert knowledge of walnut pest management in the region. Alternative pest controls and rates that performed equivalently or better than conventional grower standard controls in scientific trials were considered for inclusion in the APSs.

2.4. Cost as a metric for economic comparison

Profit, rather than cost, is often the financial indicator upon which growers base their economic decisions. This analysis, however, was centered on cost comparisons due to a strong likelihood that total revenue would not significantly change among the pest management systems analyzed. While the pricing system for walnuts is very complex and may differ among handlers, walnut growers generally receive progressively lower prices through insect damage penalties if more than 5% of the total crop has insect damage (Diamond, 2008). Thus, following concepts presented by Lichtenberg and Zilberman (1986), walnut growers exhibit a somewhat inelastic demand for damage abatement at the 5% damage threshold, where damage to more than 5% of the crop is generally not tolerated to the extent possible. Diamond Foods, a large handler in the region, reported that in 2008, 97% of the total deliveries had 5% or less insect damage, suggesting that most growers successfully practice PSs meeting the 5% threshold to avoid the insect damage penalties (Personal communication, Eric Heidman, Diamond Foods).

Therefore, while the PSs reported in the PUR database by each grower each year are likely to vary somewhat in pest control efficacy, they were likely to be below the 5% cutoff for insect damage penalties. Likewise, through the choice of hypothetical alternative pest controls that demonstrated similar efficacy to conventional controls in field trials, there was a strong likelihood that the hypothetical APSs used in the analysis would also fall within the 5% cutoff, and therefore not cause a significant change in total revenue (price or yield) from the grower's current practices. With total revenue held constant, cost became the driving metric affecting economic feasibility comparisons between the growers' currently practiced conventional PSs and the hypothetical APSs. The assumption of equivalent total revenue was further examined through a sensitivity analysis as a last step in the methodology.

2.5. Classification

Each PS was classified under five overlapping pesticide groups based on their use of (1) "Organophosphates", (2) "Pyrethroids", (3) "Combination" of organophosphates and pyrethroids, (4) "Miticides", and (5) "Alternatives". The first three non-overlapping groups represent the two main chemical classes used by walnut growers for insect control: organophosphates and pyrethroids. Each PS used one or both of these two chemical classes at some point during the year. Sorting each PS into one of these three groups allowed for an assessment of the relative environmental and economic impacts attributed to PSs employing these two chemical classes either separately or together during the growing season year.

The fourth pesticide group, Miticides, included all of the PSs currently treating for mites. Growers practicing PSs in the Miticide group were the most likely to benefit from potential improvements in biological control under an APS, since mites are often thought to be a secondary pest that can be controlled by natural enemies. The Miticide group overlapped the Organophosphate, Pyrethroid, Combination, and Alternative groups by including all PSs in the study that used miticides in addition to the other pest controls.

Similar to the Miticides group, the Alternatives group also overlapped the other four groups, including all of the PSs currently incorporating alternative products in addition to other pest controls. The role of the Alternatives group in the analysis was to identify the environmental and economic costs and benefits attributed to use of alternative products in conjunction with conventional pesticides. Alternative products were defined as those 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). Table 1 summarizes the breakdown of the five pesticide groups by defining the inclusion of organophosphate, pyrethroid, miticide, and alternative product components as either mandatory or optional in order for a PS to be classified within a given pesticide group. The optional term signified that PSs both with and without the optional component would be included in a given pesticide group – it was not a defining component of the pesticide group.

2.6. Impact of PS on water quality

To determine the water quality impact of a PS, the EIQ indices were combined with pesticide use rates to calculate an EIQ water quality impact score as follows (Kovach et al., 1992):

$$\mathrm{EIQ}_j = \frac{\sum_{i=1}^{n}(\mathrm{AI}_{ij} \times \mathrm{INDEX}_i)}{\mathrm{TRT}_j} \tag{1}$$

where j was the PS being analyzed, i represented an individual pesticide product in the PS, n was the total number of products used in the PS, AI_{ij} was the total kg of the dominant active ingredient of product i in PS_j, TRT_j was the total hectares treated by all of the pesticides, and INDEX_i was the online water quality index for the dominant active ingredient of product i, as calculated by Kovach et al. (1992). In summary, the index served as a weight on the active

Table 1
Breakdown of the five pesticide groups: M signifies a mandatory inclusion for the given pesticide group, O signifies an optional inclusion. Any PS[a] in a given pesticide group will by definition include all mandatory components, but may or may not have optional components. Any PS in the Miticides or Alternatives groups will include an organophosphate and/or pyrethroid component.

Pesticide group		PS contains the following components			
		Organophosphate	Pyrethroid	Miticide	Alternative
1	Organophosphates	M		O	O
2	Pyrethroids		M	O	O
3	Combination	M	M	O	O
4	Miticides	M: either organophosphate, pyrethroid, or both		O	
5	Alternatives			O	M

[a] PS: pest management system.

ingredient use per hectare, so that the resulting EIQ value can be used to measure relative levels of water quality impact between different PSs.

2.7. Costs of PS

The total cost per hectare of PSs included the material costs of the pest control products and the sprayer costs of applications. Products applied to the same area on the same date were assumed to be in the sprayer together. A standardized sprayer cost of \$38.47/hectare was used for all PSs, which included labor, fuel, and maintenance (Buchner et al., 2002). The following equation calculated the total cost per hectare of each PS:

$$\mathrm{COST}_j = \frac{\sum_{i=1}^{n}(\mathrm{PRD}_{ij} \times \mathrm{PRICE}_i)}{\mathrm{TRT}_j} + \left(\mathrm{SPRYR} \times \frac{38.47}{\mathrm{hectare}}\right) \quad (2)$$

where i, j, n, and TRT_j are defined in Eq. (1), PRD_{ij} is the total amount of product i used in PS_j, PRICE_i is the price of product i in US dollars per unit amount, and SPRYR_j is the total number of sprayer applications for PS_j.

After classifying each PS and calculating its impact and cost, an acceptable level of impact to water quality was used to separate PSs of higher and lower impact levels. The values of acceptable impact were based on the calculated environmental impact score of a hypothetical APS, which was created for every PS in the sample.

2.8. Hypothetical alternative strategies

Each hypothetical APS included an assortment of alternative products that target the grower's pests at a roughly equivalent efficacy to the grower's PUR-reported PS, and were considered to have a lower water quality impact due to their more selective nature. The PUR database does not require growers to report the pest targeted by a given pesticide application. It was therefore assumed that the pesticide applications reported to the PUR database were likely to be controlling the following five economically important pests in the study area, based on the opinions of regional farm advisors: codling moth, walnut husk fly (*Rhagoletis completa*), aphid (*Chromaphis juglandicola, Callaphis juglandis*), webspinning spider mites (*Tetranychus urticae, Tetranychus pacificus*), and to a lesser degree for these three counties, navel orangeworm (*Amyelois transitella*).

To determine if a PS was targeting codling moth, walnut husk fly, navel orangeworm and/or mites, the following assumptions were made about product choices and application timing reported in the PUR database in relation to the pest's life cycle: use of a broad spectrum codling moth product without bait (NuLure, Mo-Bait) between April 15th to the end of July or use of a selective codling moth product at any time indicated that the PS treated for codling moth; use of bait or a selective walnut husk fly product indicated treatment for walnut husk fly; use of a broad spectrum navel orangeworm product after September 1st or a selective navel orangeworm product at any time indicated treatment for navel orangeworm; and use of miticides indicated treatment for mites.

The products thus selected for the APSs are as follows: control for codling moth consisted of one pheromone-dispensing puffer for every 0.81 hectares. Recent efficacy trials have determined this puffer rate to be generally equivalent in effectiveness to conventional controls at low to moderate codling moth pressures (Pickel et al., 2007). For higher codling moth pressure conditions (damage >2%), an additional application of the insect growth regulator (IGR) methoxyfenozide (Intrepid 2f) was included as a supplement (Coates et al., 2001; UC-IPM, 2008). For PSs controlling walnut husk fly, the APS included three applications of spinosad (Success) with bait (NuLure), applied to every other row (Van Steenwyk et al., 2005b). APS controls for secondary pests such as aphids and mites consisted of an application of acetamiprid (Assail) or etoxazole (Zeal), respectively (Van Steenwyk et al., 2005a; UC-IPM, 2008). For the few PSs that indicated a navel orangeworm problem, a late season application of methoxyfenozide was added to the APS (Grafton-Cardwell et al., 2005; UC-IPM, 2008) (Table 2).

2.8.1. Codling moth pressure and aphid treatment

While product choice, application timing, and pest life cycle was sufficient to determine most of the pests that a PS was likely targeting, this method did not work well for two variables that were needed for the analysis, aphid control and codling moth pressure level. The product choices and timing for aphid control overlap substantially with those for codling moth, and thus could not be easily separated by product or application date. Similarly, the PUR data was not suitable for identifying codling moth pressure levels, which must be determined in order to ascertain if an IGR application is needed to supplement pheromone treatment in the hypothetical APS.

Four different aphid-treatment/moth-pressure scenarios were created, using responses from an unpublished survey sent to walnut growers in the three counties in 2006. The responses to the following two survey questions were used to define the scenarios: first, growers were asked if they treated for aphid "rarely/never", "occasionally/sometimes" or "always/every year." The first response was interpreted as 'no', and the latter two responses were treated as 'yes'. The second survey question asked growers for the typical number of codling moth generations they experienced during the season, and the response was used as a proxy for codling moth pressure. Moth pressure was defined as either 'low to moderate' (0–2 generations) or 'high' pressure (3+ generations). The use of moth generations as a measure of pest pressure followed the methodology employed by Norwood and Marra (2003), which used pesticide application frequency as a proxy. In this study, moth generations were used instead, due to the numerous regulations limiting the number of applications of certain pesticides, thus limiting the usefulness of application frequency as a proxy for pressure.

Table 2
Products, rates, and prices used in APSs.[e]

Pest control	Use rate (per hectare)	Price	Number of applications per season					
			Codling moth		Walnut husk fly	Mite[d]	Navel orangeworm	Aphid[c, d]
			Low[a]	High[b]				
Pheromone (puffer)	1 puffer/0.81 hectares	$120/puffer	1	1				
Methoxyfenozide (intrepid 2f)	1.2 l	$85/liter		1			1	
Spinosad (success)	0.23 l	$223.49/liter			3			
Bait (NuLure)	3.5 l	$6.32/liter			3			
Etoxazole (Zeal)	0.21 kg	$1132.29/kg				1		
Acetamiprid (Assail)	0.26 kg	$576/kg						1
Puffer installation		$25/hectare	1	1				
Sprayer application cost		$38.47/hectare						

[a] Low: low to moderate moth pressure assumption (LN, LY aphid/moth pressure scenarios).
[b] High: high moth pressure assumption (HN, HY aphid/moth pressure scenarios).
[c] Not included under LN and HN aphid/moth pressure scenarios.
[d] Not included when biological control assumed to be effective (L, H scenarios), APS_{BIO}.
[e] APS = alternative pest management system.

The following four scenarios were then created based on possible answer combinations: low/moderate moth pressure, no aphid (LN); low/moderate moth pressure, yes aphid (LY); high moth pressure, no aphid (HN); and high moth pressure, yes aphid (HY). Under each of these four aphid/moth scenarios, the APS was modified slightly. For the two low to moderate moth pressure scenarios, LN and LY, pheromone alone was considered sufficient to control codling moth. Under the two high pressure scenarios, HN and HY, a supplemental application of methoxyfenozide was included in the APSs. For the two scenarios requiring treatment for aphids, LY and HY, the alternative aphicide, acetamiprid, was included in the APSs, whereas it was not included in the two scenarios without aphid treatments, LN and HN (Table 2, superscripts a–c).

2.9. Cost and water quality impact comparison

The following equations were used to derive weighted averages for the water quality EIQ score differences and cost differences between the PS and the four scenario modifications of the APS, respectively:

$$\begin{aligned}\mathrm{EIQ}_{\mathrm{wtdDIFF},j} &= \mathrm{LN}_{\mathrm{wt}}(\mathrm{EIQ}_{\mathrm{PS},j} - \mathrm{EIQ}_{\mathrm{LN},j}) + \mathrm{HN}_{\mathrm{wt}}(\mathrm{EIQ}_{\mathrm{PS},j} - \mathrm{EIQ}_{\mathrm{HN},j}) \\ &\quad + \mathrm{LY}_{\mathrm{wt}}(\mathrm{EIQ}_{\mathrm{PS},j} - \mathrm{EIQ}_{\mathrm{LY},j}) + \mathrm{HY}_{\mathrm{wt}}(\mathrm{EIQ}_{\mathrm{PS},j} - \mathrm{EIQ}_{\mathrm{HY},j}) \end{aligned} \quad (3)$$

$$\begin{aligned}\mathrm{COST}_{\mathrm{wtdDIFF},j} &= \mathrm{LN}_{\mathrm{wt}}(\mathrm{COST}_{\mathrm{PS},j} - \mathrm{COST}_{\mathrm{LN},j}) + \mathrm{HN}_{\mathrm{wt}}(\mathrm{COST}_{\mathrm{PS},j} \\ &\quad - \mathrm{COST}_{\mathrm{HN},j}) + \mathrm{LY}_{\mathrm{wt}}(\mathrm{COST}_{\mathrm{PS},j} - \mathrm{COST}_{\mathrm{LY},j}) \\ &\quad + \mathrm{HY}_{\mathrm{wt}}(\mathrm{COST}_{\mathrm{PS},j} - \mathrm{COST}_{\mathrm{HY},j}) \end{aligned} \quad (4)$$

where j was defined in Eq. (1), LN_{wt}, HN_{wt}, LY_{wt} and HY_{wt} were weights defined as the percentage of surveyed growers falling under each of the four aphid/moth scenarios, $EIQ_{PS,j}$ and $COST_{PS,j}$ were the values calculated in Eqs. (1) and (2) for the PS, respectively, and $EIQ_{LN,j}$, $EIQ_{HN,j}$, $EIQ_{LY,j}$, $EIQ_{HY,j}$, $COST_{LN,j}$, $COST_{HN,j}$, $COST_{LY,j}$, and $COST_{HY,j}$ were the EIQ scores and cost values calculated in Eqs. (1) and (2) respectively for the hypothetical APSs under each of the four aphid/moth scenarios.

The resulting $EIQ_{wtdDIFF}$ and $COST_{wtdDIFF}$ values indicated whether each PS had a higher or lower water quality impact and cost than its respective APS. An $EIQ_{wtdDIFF}$ value equal to zero signified that the PS was currently at the acceptable water quality impact level. A negative $EIQ_{wtdDIFF}$ indicated that the PS was below the acceptable impact level with a lower EIQ than the APS. A positive $EIQ_{wtdDIFF}$ value indicated that the PS was above the acceptable water quality impact level, with a higher impact than the APS. The average $EIQ_{wtdDIFF}$ of PSs above and below zero and the numbers of PSs in each pesticide group were calculated in order to identify the PSs most in need of lowering water quality impact.

2.10. Changes in costs

The next step was to examine the $COST_{wtdDIFF}$ values in order to determine how a grower's cost might change if they were to lower water quality impact to an acceptable level by replacing their PS with the hypothetical APS. Thus, only the PSs with high water quality impact (positive $EIQ_{wtdDIFF}$) were analyzed. A $COST_{wtdDIFF}$ value of zero meant that there was no difference in cost between the PS and APS, while a positive value meant that the PS had a higher cost, and a negative value signified a lower cost of the PS relative to the APS. Growers practicing PSs with positive values of $COST_{wtdDIFF}$ could therefore see a cost savings if they were to lower water quality impact by switching to the APS, whereas growers with PSs having a negative $COST_{wtdDIFF}$ would realize a cost increase, or tradeoff, associated with improving water quality. Similar to the process for water quality impact, the average $COST_{wtdDIFF}$ of PSs above and below zero were calculated, as well as the number of PSs in each pesticide group.

2.11. Biological control efficacy

With a snapshot now created of how different types of PSs compare environmentally and economically to APSs of roughly similar efficacy, the potential influence that biological control could have on water quality impact and costs was factored in. Of the five pests examined in this analysis, mites and aphids, often referred to as secondary pests, appeared to have the most promise as candidates for biological control (ANR, 2003). The previous EIQ and cost calculations were repeated using APSs without miticides or aphicides (APS_{BIO}), assuming naturally occurring biological control for these two pests (Table 2, superscript d). The new EIQ and cost difference values, $EIQ_{wtdDIFF\_BIO}$ and $COST_{wtdDIFF\_BIO}$, were calculated as follows:

$$\mathrm{EIQ}_{\mathrm{wtdDIFF\_BIO},j} = L_{\mathrm{wt}}(\mathrm{EIQ}_{\mathrm{PS},j} - \mathrm{EIQ}_{L,j}) + H_{\mathrm{wt}}(\mathrm{EIQ}_{\mathrm{PS},j} - \mathrm{EIQ}_{H,j}) \quad (5)$$

$$\mathrm{COST}_{\mathrm{wtdDIFF\_BIO},j} = L_{\mathrm{wt}}(\mathrm{COST}_{\mathrm{PS},j} - \mathrm{COST}_{L,j}) + H_{\mathrm{wt}}(\mathrm{COST}_{\mathrm{PS},j} - \mathrm{COST}_{H,j}) \quad (6)$$

where L_{wt} and H_{wt} were weights defined as the percentage of surveyed growers falling under low to moderate (L = LN plus LY) or high (H = HN plus HY) codling moth pressure scenarios, $EIQ_{PS,j}$ and $COST_{PS,j}$ were defined in Eqs. (3) and (4) respectively, and $EIQ_{L,j}$, $EIQ_{H,j}$, $COST_{L,j}$, and $COST_{H,j}$ were the EIQ scores and cost values calculated using Eqs. (1) and (2), respectively, for the hypothetical miticide- and aphicide-free APS_{BIO}s under low to moderate (L) or high (H) moth pressure scenarios. The average $COST_{wtdDIFF\_BIO}$ and $EIQ_{wtdDIFF\_BIO}$ of PSs above and below zero and the numbers of PSs in each pesticide group were calculated for comparison with the values obtained when miticides and aphicides were included in the APS.

2.12. Identification and quantification of factors influencing tradeoffs

The previous steps yielded a number of insights into the potential tradeoffs between environmental and economic concerns, such as the proportion of currently used PSs with water quality impact above a defined acceptable level, the pesticide groups with highest impact, whether costs would increase or decrease if the PS was replaced by an alternative strategy, and how biological control efficacy affected these numbers. The next step was then to create a regression model to determine the relative influence of various underlying factors that affected whether costs increased or decreased when the PS was replaced by the APS. If the cost of pest management fell, then there was no tradeoff between economic costs and water quality, as both the grower and the environment benefited. However, if the cost of pest management rose, then there was a tradeoff between higher costs for the grower and improved water quality. The six factors identified as influencing this tradeoff were as follows: the number of pests targeted by a PS without potential to be successfully controlled biologically (NOBIO), the cost per hectare of organophosphates (OP), the cost per hectare of pyrethroids (PYR), the cost per hectare of miticides (MITE), the cost per hectare of alternative products (ALT), and biological control efficacy.

The NOBIO variable represented the number of the pests that a grower treated for that were not considered to be candidates for effective biological control, including codling moth, walnut husk fly, and navel orangeworm. A PS could therefore have a NOBIO value of one, two, or three, depending on whether it controlled walnut husk fly and/or navel orangeworm in addition to codling moth. The NOBIO variable reflected a potential source of increasing costs upon switching from a PS to an APS_{BIO}. The treatment of the three NOBIO pests under an APS_{BIO} required separate applications of selective pest controls due to life cycle timing requirements and a generally higher pest-specific selectivity of the alternative products. In contrast, many conventional controls in the PSs were broad spectrum, and could be used to simultaneously control multiple pests at once. Thus, a grower with multiple NOBIO pests would likely see an increase in the number of applications of pest controls per year upon replacing a PS with an APS, leading to higher costs.

The OP, PYR, MITE, and ALT variables represented the portion of the total cost per hectare of the PS attributed to organophosphates, pyrethroids, miticides, and alternative products, respectively, which were the four components of the pesticide groups listed as column headings in Table 1. These variables thus represented the magnitude that each of the four components contributed to any tradeoff or savings that might have occurred upon replacing a PS with an APS_{BIO}. MITE served a dual purpose, not only representing the cost per hectare of miticide use, but also indicating that the PS treated for a pest that could be controlled biologically, thereby improving the chances of cost savings upon lowering water quality impact. Finally, biological control efficacy was brought into the regression through use of $COST_{wtdDIFF\_BIO}$, calculated in Eq. (6), as the dependent variable representing the tradeoff or savings realized upon replacing a PS with an APS_{BIO} under the assumption of effective biological control. Using JMP version 8, the following model was chosen through a combination of Akaike's Information criterion (AIC) and Mallow's C_p criterion (JMP, 2009):

$$\begin{aligned} COST_{wtdDIFF\_BIO} = {} & \mathit{INTERCEPT} + NOBIO + ALT + MITE + OP \\ & + PYR + NOBIO * NOBIO + ALT * ALT \\ & + MITE * MITE + OP * OP + PYR * PYR \\ & + ALT * NOBIO + ALT * MITE + ALT * OP \\ & + ALT * PYR + MITE * NOBIO + MITE * OP \end{aligned} \tag{7}$$

The polynomial was centered to reduce collinearity due to the inclusion of quadratic terms, and was checked using variance inflation factor (VIF) methods. A bootstrap procedure of 500 random samples with replacement was then employed, with random sampling of all X and Y pairings. The reflection method was used to estimate precision through the creation of confidence intervals for each parameter.

2.13. Sensitivity analysis of total revenue assumption

As a final step, the sensitivity of the percentage of PSs that resulted in a profit increase upon replacement with an APS or APS_{BIO} to the assumption of equivalent total revenue between the PS, APS, and APS_{BIO} was analyzed. A representative total revenue of \$12,602/ha (\$1.87/kg * 6725 kg/ha) was assigned to the 2531 PSs in the sample (Grant et al., 2007). The profit of each PS was then estimated as the total revenue minus cost

$$\pi_{PS_{,j}} = (\$12,602) - COST_{PS,j} \tag{8}$$

where j was the PS being analyzed, $\pi_{PS_{,j}}$ was the profit per hectare of each of the 2531 PSs, and $COST_{PS,j}$ was the cost per hectare of each PS, as calculated in Eq. (2).

Based on the criteria used to select alternative products for inclusion in the APS and APS_{BIO}, insect damage, yield, and therefore total revenue should remain similar to that of the current PS upon replacement with the alternatives. If, however, insect damage was significantly greater with the use of the APS or APS_{BIO} compared to the current PS, then total revenue would decrease. To understand the effect that a decrease in total revenue could have on the potential for savings upon replacement of a PS with an alternative system, the change in profit for each of the 2531 PSs upon replacement by either the APS or APS_{BIO} was calculated using 11 different total revenue levels. The first level met the assumption of constant total revenue between the PS and the APS or APS_{BIO}, with 0% decrease. The next 10 total revenue levels functioned as the sensitivity analysis, incrementally decreasing the total revenue by 1%. Hence, the first level, with 0% decrease, was the representative total revenue of \$12,602/ha, while the last level, with a 10% decrease, was \$11,342/ha.

$$\pi_{APS_{,j,k}} = (\$12,602 - (\%_k * \$12,602)) - COST_{APS,j} \tag{9}$$

$$\pi_{APSBIO_{,j,k}} = (\$12,602 - (\%_k * \$12,602)) - COST_{APSBIO,j} \tag{10}$$

where $\%_k$ is a 0.01 incremental decrease from $k = 0$ to 0.10; $\pi_{APS_{,j,k}}$ and $\pi_{APSBIO_{,j,k}}$ were the profit per hectare if the PS was replaced by the APS or APS_{BIO}, respectively, and the total revenue was decreased by k, and $COST_{APS,j}$ and $COST_{APSBIO,j}$ were the costs per hectare of the APS and the APS_{BIO}, as calculated using Eq. (2). The change in profit for each of the 11 total revenue levels was the difference between the APS or APS_{BIO} and the PS

$$\pi_{Change,APS_{,j},k} = \pi_{APS_{,j,k}} - \pi_{PS_{,j}} \tag{11}$$

$$\pi_{Change,APSBIO,j,k} = \pi_{APSBIO_{,j,k}} - \pi_{PS_{,j}} \tag{12}$$

The percentages of $\pi_{Change,APS,j,k}$ and $\pi_{Change,APSBIO,j,k}$ greater than or equal to zero were then plotted against each of the 11 incremental decreases in total revenue in order to graphically visualize how the percentage of PSs that resulted in a profit increases upon replacement with an APS or APS_{BIO} changed with decreasing total revenue.

3. Results

3.1. Proportion of PSs in pesticide groups

As shown in the second column of Table 3, over 90% of the 2531 PSs analyzed used organophosphates, with 1300 in the Organophosphate pesticide group, and 1035 in the Combination group. Nearly 50% (n = 1231) of the PSs used pyrethroids, with 196 in the Pyrethroid group and the remaining 1035 in the Combination group. Finally, almost 70% (n = 1714) of PSs used miticides, while 13% (n = 322) used alternatives.

3.2. PSs with probable high water quality impact

The water quality impact scores of almost every PS in the Organophosphate (100%) and Combination (99.7%) groups were higher than the impact level of their associated APS (positive $EIQ_{wtdDIFF}$ values), indicating a need to lower water quality impact scores in order to achieve the acceptable level defined by the APS. Similarly, over 95% of the PSs in both the Miticide (98%) and Alternative (96%) groups had higher water quality impacts than the APS. PSs in the Pyrethroid group differed, however, with approximately half showing impacts above (51%) and half below (49%) their APS impact levels. In total, 96% of PSs appeared to be potential candidates for lowering impact to water quality, averaging 91 EIQ units above the APS impact level, as represented by the average $EIQ_{wtdDIFF\_BIO}$. The remaining 4% of PSs averaged two EIQ units below the APS level, and were therefore considered to have adequately low water quality impact (Table 3).

3.3. Changes in cost to lower water quality impact

Looking solely at the 2432 PSs identified as having a higher water quality impact than the acceptable level of their APS, the analysis revealed that 96% (n = 2345) of the PSs were currently less expensive than their APS counterparts. Thus, the growers practicing these PSs would experience an average cost increase of $118 per hectare (average $COST_{wtdDIFF}$) upon substitution of the PS with the APS. There was little difference in results between pesticide groups, with more than 90% of the PSs in every group having lower costs than the corresponding APSs. The remaining 4% of PSs had costs above that of their APSs. The growers practicing these PSs could have realized an average cost savings of $79 per hectare while lowering water quality impact by using an APS (Table 4). Consequently, in the vast majority of cases, growers would have faced a tradeoff between increased costs and improved water quality.

3.4. The importance of biological control

The substitution of naturally occurring biological control for the miticide and aphicide in the hypothetical APS_{BIO}s eliminated all miticide and aphicide costs, and thus exerted a much stronger effect on cost than was seen on water quality impact. This result was expected, due to the relatively low water quality EIQ scores and high costs of the miticide and aphicide chosen for the APSs. The slight decrease of the APS_{BIO} impact values caused by the elimination of the miticide and aphicide resulted in an increase in the percentage of PSs higher than their APS_{BIO} impact level from 96% to 97%. Most of this change occurred among the PSs in the Pyrethroid group, which saw an increase in the percentage of PSs higher than their APS_{BIO} impact level from 51% to 62%. Average $EIQ_{wtdDIFF\_BIO}$ changed little under assumptions of biological control efficacy, with no change for PSs with values higher than that of the APS_{BIO}s (91 units higher), and a decrease from two to one units for those with impact values lower than that of the APS_{BIO} (comparison between Tables 3 and 5).

A strong effect of biological control efficacy was seen on costs, since the cost of the APS_{BIO} was lower than that of the APS due to the elimination of miticide and aphicides. The percentage of PSs with costs greater than the hypothetical alternative system increased from 4% with the APS to 44% with the APS_{BIO}. The growers practicing these PSs would have experienced an average cost savings of $128 per hectare upon substituting the APS_{BIO} for the PS to lower water quality impact. The percentage increase in PSs that had higher costs relative to their APS_{BIO}, and thus potential cost savings for the growers practicing them, was highest in the Miticide pesticide group, where percentages increased by 55% (from 4% to 59%), followed by a 46% increase in the Combination group (from 5% to 51%), a 40% increase in the Alternative group (from 8% to 48%), a 36% increase in the Organophosphate group (from 3% to 39%), and a 36% increase in the Pyrethroid group (from 0% to 36%). The remaining 56% of the PSs had costs lower than that of the APS_{BIO}. However, although the growers practicing these PSs would not experience a savings upon use of the APS_{BIO}, the average magnitude of their cost increase fell by 53% from $292 to $138 per hectare (comparison between Tables 4 and 6).

Table 3
Number and percentage of PSs[c] with water quality impact above and below that of their associated APS,[d] by pesticide groups and total sample. Average water quality EIQ[e] unit per acre difference between the PSs and APSs.

Pesticide groups	Total	Higher than APS impact value		Lower than APS impact value	
		Number	Percentage	Number	Percentage
Organophosphate	1300	1300	100	0	0
Combination	1035	1032	100	3	0.3
Pyrethroid	196	100	51	96	49
Total sample[a]	**2531**	**2432**	**96**	**99**	**4**
Miticide	1714	1674	98	40	2
Alternative	322	308	96	14	4
Average EIQ units above/below that of the APS[b]					
	91			2	

[a] The numbers in the Organophosphate, Combination, and Pyrethroid groups sum to the total sample. (Miticide and Alternative groups can overlap the previous three groups and each other.)
[b] Absolute value of the average $EIQ_{wtdDIFF}$ (unit = Index weighted use rate: index * kgs/hectare).
[c] PS = Pest management system.
[d] APS = alternative pest management system.
[e] EIQ = Environmental Impact Quotient score.

Table 4
Number and percentage of PSs[c] with costs above and below that of their associated APS,[d] by pesticide groups and total sample. Average cost per hectare difference between the PSs and APSs.

Pesticide groups	Total	Higher than APS cost value		Lower than APS cost value	
		Number	Percentage	Number	Percentage
Organophosphate	1300	37	3	1263	97
Combination	1032	50	5	982	95
Pyrethroid	100	0	0	100	100
Total sample[a]	**2432**	**87**	**4**	**2345**	**96**
Miticide	1674	60	4	1614	96.
Alternative	308	25	8	283	92
Average dollars per hectare above/below that of the APS[b]					
		79		292	

[a] The numbers in the Organophosphate, Combination, and Pyrethroid groups sum to the total sample. (Miticide and Alternative groups can overlap the previous three groups and each other.)
[b] Absolute value of the average $COST_{wtdDIFF}$ (unit = dollars per hectare).
[c] PS = pest management system.
[d] APS = alternative pest management system.

Table 5
Biological control: number and percentage of PSs[c] with water quality impact above and below that of their associated APS,[d] by pesticide groups and total sample. Average water quality EIQ[e] unit per hectare difference between the PSs and APSs, when biological control replaces miticide and aphicide costs in APS.

Pesticide groups	Total	Higher than APS impact value		Lower than APS impact value	
		Number	Percentage	Number	Percentage
Organophosphate	1300	1300	100	0	0
Combination	1035	1034	100	1	0.1
Pyrethroid	196	121	62	75	38
Total sample[a]	**2531**	**2455**	**97**	**76**	**3**
Miticide	1714	1688	99	26	2
Alternative	322	311	97	11	3
Average EIQ units above/below that of the APS: biological control effective[b]					
		91		1	

[a] The numbers in the Organophosphate, Combination, and Pyrethroid groups sum to the total sample. (Miticide and Alternative groups can overlap the previous three groups and each other.)
[b] Absolute value of the average $EIQ_{wtdDIFF\_BIO\_}$ (unit = index weighted use rate: index * kgs/hectare).
[c] PS = pest management system.
[d] APS = alternative pest management system.
[e] EIQ = Environmental Impact Quotient score.

3.5. Influential factors on tradeoffs between cost and water quality impact

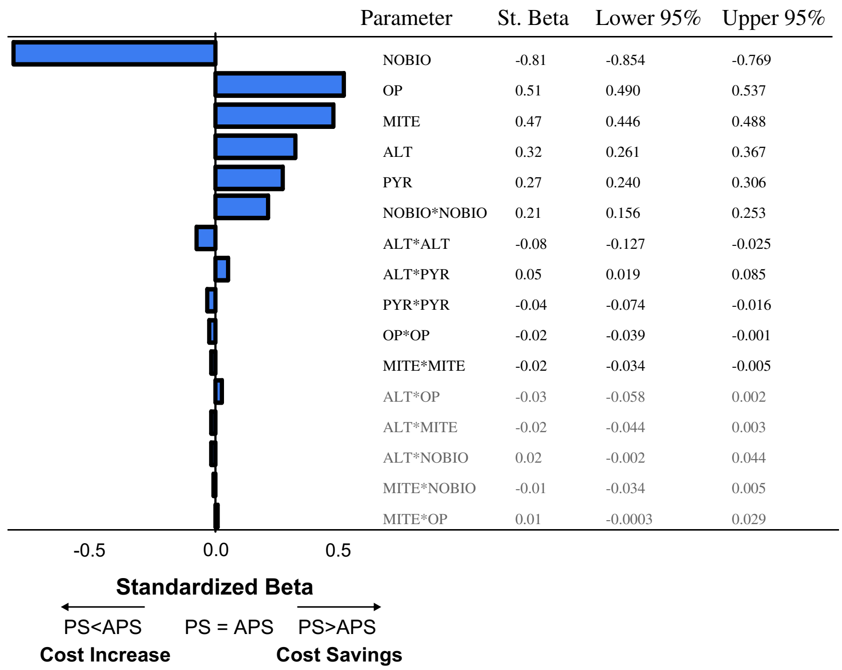
The previous results showed that biological control efficacy played an important role in the economic tradeoffs associated with lowering water quality impact. The regression model then deepened this understanding by quantifying the importance of the underlying factors influencing whether a grower would experience a cost increase or decrease upon lowering water quality impact if biological control was effective.

The effect of NOBIO had the largest magnitude, with a standardized beta (SB) coefficient of −0.81. The magnitude and sign signified that as the number of pests that are not candidates for biological control increased, $COST_{wtdDIFF\_BIO}$ shifted to the left on the number line shown in Fig. 1. Thus, an increase in the number of NOBIO pests decreased the likelihood that growers would realize any savings upon switching from a PS to an APS_{BIO}, and greatly increased the chance of experiencing a tradeoff to improving water quality in the form of a cost increase. The NOBIO * NOBIO coefficient was positive (SB: 0.21), however, signifying that $COST_{wtd-}$

Table 6
Biological control: number and percentage of PSs[c] with costs above and below that of their associated APS,[d] by pesticide groups and total sample. Average cost per hectare difference between the PSs and APSs, when biological control replaces miticide and aphicide costs in APS.

Pesticide groups	Total	Higher than APS cost value		Lower than APS cost value	
		Number	Percentage	Number	Percentage
Organophosphate	1300	511	39	789	61
Combination	1034	524	51	510	49
Pyrethroid	121	43	36	78	65
Total sample[a]	**2455**	**1078**	**44**	**1377**	**56**
Miticide	1688	993	59	695	41
Alternative	311	149	48	162	52
Average dollars per hectare above/below that of the APS: biological control effective[b]					
		128		138	

[a] The numbers in the Organophosphate, Combination, and Pyrethroid groups sum to the total sample. (Miticide and Alternative groups can overlap the previous three groups and each other.)
[b] Absolute value of the average $COST_{wtdDIFF\_BIO}$ (unit = dollars per hectare).
[c] PS = pest management system.
[d] APS = alternative pest management system.



Parameter	St. Beta	Lower 95%	Upper 95%
NOBIO	-0.81	-0.854	-0.769
OP	0.51	0.490	0.537
MITE	0.47	0.446	0.488
ALT	0.32	0.261	0.367
PYR	0.27	0.240	0.306
NOBIO*NOBIO	0.21	0.156	0.253
ALT*ALT	-0.08	-0.127	-0.025
ALT*PYR	0.05	0.019	0.085
PYR*PYR	-0.04	-0.074	-0.016
OP*OP	-0.02	-0.039	-0.001
MITE*MITE	-0.02	-0.034	-0.005
ALT*OP	-0.03	-0.058	0.002
ALT*MITE	-0.02	-0.044	0.003
ALT*NOBIO	0.02	-0.002	0.044
MITE*NOBIO	-0.01	-0.034	0.005
MITE*OP	0.01	-0.0003	0.029

Fig. 1. Magnitude, sign and 95% confidence intervals of regression parameters (grayed-out values are not significant). Please see Appendix A for complete list of acronym definitions.

$_{\mathrm{DIFF\_BIO}}$ was shifting to the left at a decreasing rate as the number of non-biologically controlled pests increased (Fig. 1).

After NOBIO, OP (SB: 0.51) had the next largest effect, followed by MITE (SB: 0.47), ALT (SB: 0.32), and PYR (SB: 0.27). The positive sign of the coefficients reflected that as the proportion of the cost of the PS attributed to each of the four pesticide components increased, $\mathrm{COST_{wtdDIFF\_BIO}}$ shifted to the right on the number line shown in Fig. 1. Thus, as each component increased, there was a stronger likelihood that growers would see savings upon switching from a PS to an $\mathrm{APS_{BIO}}$, or at least a lower tradeoff to improving water quality. The coefficients of the quadratic terms ALT $*$ ALT (SB: -0.08), PYR $*$ PYR (SB: -0.04), OP $*$ OP (SB: -0.02), and MITE $*$ MITE (SB: -0.08) were all negative, though with very small magnitudes, indicating that $\mathrm{COST_{wtdDIFF\_BIO}}$ was shifting to the right at a slightly decreasing rate as each variable increased (Fig. 1).

All interaction terms were non-significant, as their confidence intervals spanned small ranges around zero, with the exception of ALT $*$ PYR (SB: 0.05), which had a positive coefficient of small magnitude (Fig. 1). The significance of this interaction term is most likely due to the fact that there was never any use of both alternative and pyrethroid products when PYR was at low levels, defined as values lower than the PYR mean. When PYR was at high levels (values greater than or equal to its mean), it was positively affected by ALT: the $\mathrm{COST_{wtdDIFF\_BIO}}$ values changed from cost increases (negative $\mathrm{COST_{wtdDIFF\_BIO}}$) associated with high PYR and low ALT, to cost savings (positive $\mathrm{COST_{wtdDIFF\_BIO}}$) associated with high PYR and high ALT.

3.6. Sensitivity of results to total revenue assumption

Fig. 2 shows the results of the sensitivity analysis regarding how the percentage of instances of profit increases upon replacement of a PS with an APS or $\mathrm{APS_{BIO}}$ might change if total revenue did not remain the same, as was assumed. Under the assumption of equivalent total revenue between the PS, APS, and $\mathrm{APS_{BIO}}$ (0% decrease in total revenue), profit increased for 4% of PSs when replaced by an APS, and for 44% of PSs upon replacement with an $\mathrm{APS_{BIO}}$. These percentages are the exact same as the percentages of cost savings reported in Tables 4 and 6, as cost was the driving economic metric under the constant total revenue assumption. As this assumption is relaxed, the percentages of instances of profit increase upon switching to an alternative system drop, zeroing at 4% and 6% total revenue decreases for APS and $\mathrm{APS_{BIO}}$, respectively (Fig. 2).

4. Discussion

4.1. Codling moth, walnut husk fly, and navel orangeworm

The presence or absence of the three pests that were not considered candidates for biological control (codling moth, walnut husk fly, and navel orangeworm) had the largest influence on whether there would be a cost increase or a cost savings upon replacement of a PS by an $\mathrm{APS_{BIO}}$ to lower water quality impact. The benefits in cost reduction that were seen through the assumption of effective biological control of mite and aphid were somewhat masked as the number of separate applications of selective pesticides for the other three pests increased. Thus growers practicing PSs targeting lower numbers of these three pests were more likely to experience cost savings upon lowering water quality impact.

4.2. Organophosphates

In general, organophosphate products tended to contribute heavily to both PS costs and water quality impact. As the most popular component of most PSs, they often formed the bulk of the total pesticide use, driving up costs so that they either were close to or exceeded that of the APS and $\mathrm{APS_{BIO}}$. Thus, growers practicing PSs with high organophosphate costs were more likely to experience cost savings upon replacement of the PS with an APS or $\mathrm{APS_{BIO}}$.

4.3. Miticides

While not quite as ubiquitous as organophosphates, miticides were used by 70% of the PSs analyzed, and thus played an important role in tradeoffs associated with improving water quality.

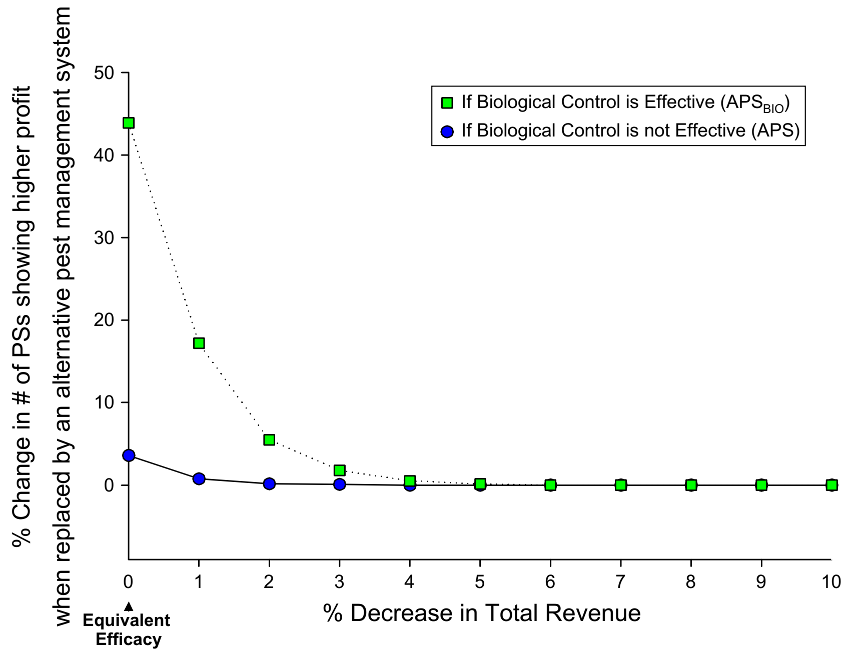


Fig. 2. Percentage change in number of pest management systems (PSs) that resulted in a profit increase upon replacement with an alternative pest management system as the estimate of total revenue decreases. The alternative pest management systems were evaluated with (APS_{BIO}) and without (APS) the assumption of effective biological control.

Many miticide products were relatively expensive compared to organophosphates and pyrethroids, and had high water quality impact. Thus, they were often a key element in determining whether the replacement of a PS by an APS or APSBIO resulted in a cost increase or decrease. The alternative miticide, etoxazole, in the APS was often more expensive than any of the miticides in the PSs, thus leading to economic tradeoffs upon replacement of the PS with the APS. In contrast, replacement of the PS by the APS_{BIO} often led to cost savings for the grower, due to the elimination of miticides in favor of biological control. If the cost and impacts of aphid controls could have been measured directly, rather than employing a weighted average due to data limitations, the results would have probably been very similar to that of miticides. In general, PSs targeting mites and/or aphids had a high probability of cost decreases upon replacement with the APS_{BIO}, if biological control was effective.

4.4. Alternative products

Alternative products tended to be relatively expensive, but had lower water quality impact than the conventional products in the PSs. Assuming that the alternative product was used as a replacement for a pyrethroid or organophosphate, the alternative products generally lowered/maintained water quality impact scores while raising costs if replacing a pyrethroid, and lowered water quality impact scores while raising/maintaining costs if replacing an organophosphate. However, as seen by the results of this analysis, this increase in the costs of the alternative products may be offset by decreases in the costs of secondary pest controls, if the use of alternative products allows for effective biological control.

4.5. Pyrethroid products

Based on the results, pyrethroids appear to have both low costs and low water quality impact. Of the 4% of PSs that had water quality impact levels below their APS, and thus were considered acceptable, most were in the Pyrethroid pesticide group. Pyrethroids generally have very low fish LC_{50}s (i.e. high toxicity) and high runoff potential via sediment transport, but very low use rates. Thus, while the EIQ model generally assigns pyrethroids the highest impact rank for both toxicity and runoff, the low use rate results in relatively low EIQ scores. However, while the pyrethroid use by any one grower has a relatively low impact on water quality, the combined use by many growers within the watershed, in addition to urban uses, exerts a cumulative negative effect on water quality. This effect is seen in the growing number of scientific documents linking pyrethroids to water quality degradation (Bacey et al., 2004; Weston et al., 2004; CDPR, 2005; Oros and Werner, 2005). Thus, pyrethroid PSs cannot be considered as a long-term solution for reducing water quality impact.

4.6. Biological control efficacy

The results show that a simultaneous environmental and economic long-run sustainable solution is largely based on effective natural biological control. While many studies on biological control have been undertaken, its efficacy at reducing or eliminating the need for pesticides is far from conclusive. Complexities such as intraguild predation, adequate natural enemy habitat, sufficient prey, and timing can all strongly affect outcomes. It is therefore difficult to predict whether a grower would see any economic benefit due to biological control when using solely selective pest controls. However, as research continues to progress, biological control may some day become a more consistently effective tool in the growers' arsenal against pests. Currently, growers may face a steep and costly learning curve, as they discover by trial and error how to best exploit biological control under their particular agricultural and environmental circumstances. Nonetheless, this learning process may be worth the effort if the potential economic and environmental benefit is significant.

4.7. Sensitivity of results to assumptions

The results of this analysis were highly sensitive to two key assumptions: (1) that total revenue will remain the same upon replacing a PS with an APS or $APS_{BIO;}$ and (2) that the use of selective low impact products will allow biological control to be effective enough to eliminate the need for miticides and aphicides. The sensitivity of the results to total revenue was evident from the rapid decrease in the percentage of instances of economic benefit upon lowering impact when total revenue decreased. While the laboratory and field trial criteria used for selection of alternative products to be included in the APS and APS_{BIO} implied low potential for decreases in total revenue, the effectiveness when implemented by growers may vary widely. Therefore, the results must be viewed as a representative estimate, based on the best available data.

The results were also very sensitive to biological control effectiveness. Given the uncertainty regarding the efficacy of biological control at reducing the need for pesticides, the results of this paper strongly support the need for further research regarding the implementation of effective biological control. The results showed that effective biological control can improve the economic feasibility of alternative pest management systems for nearly half of the sample analyzed. While ecological research on natural enemy-pest dynamics continues to progress, such studies seldom address the applied questions needed to assist growers in implementing biological control effectively. The results of this paper therefore strongly advocate the commitment of future research resources toward assisting growers in the use of biological control as an effective tool in promoting long-run agro-ecological sustainability.

4.8. Alternative solutions to lowering water quality impact

While this analysis focused on switching from high impact to low impact pesticide products, there are alternative means of reducing the negative effects of pest management on water quality. For example, certain best management practices (BMPs), may be preferable for growers who are currently practicing PSs with high water quality impact, but with costs considerably lower than that of the associated APS or APS_{BIO}. BMPs such as vegetated buffers or improvements in spray and irrigation efficiency have shown promise in preventing offsite movement of chemicals into water supplies, and therefore offer another route to lowering water quality impact not covered in this paper. These BMPs could be implemented in conjunction with either the current PS or with the APS or APS_{BIO}, depending on the grower's particular agricultural and environmental circumstances.

Furthermore, there are many government financial incentives available to assist growers in implementing low impact pest management practices. These incentives may help to reduce any economic tradeoffs in the form of cost increases associated with lowering impact. Details about financial incentives can be found through the Conservation Reserve Program (CRP), the Environmental Quality Incentive Program (EQIP), the Wetlands Reserve Program, the Wildlife Habitat Incentives Program, the Conservation Stewardship Program (formerly the Conservation Security Program), the Cooperative Conservation Partnership Initiative (CCPI), the Agricultural Management Assistance, the Partners for Fish and Wildlife, and the Water quality trading guide put out by the Conservation Technology Information Center (CTIC) (CTIC, 2006; FWS, 2009; NRCS, 2009).

5. Conclusion

The implications of the results of this study can be summarized as follows: most of the pest management systems practiced by walnut growers from 2000 to 2006 in the San Joaquin valley region of California were likely to impact water quality. The substitution of alternative pest controls (APS) could substantially lower water quality impact EIQ scores, but resulted in an economic tradeoff in the form of a cost increase for most growers. If biological control could replace the need for miticides and aphicides, this tradeoff could be replaced by cost savings for nearly half of the growers analyzed. This cost savings would most likely be realized by growers with low numbers of pests that are not candidates for biological control and relatively high use rates of organophosphates and miticides. Thus, biological control should be an important consideration in the pest management cost calculations undertaken by walnut growers, and should also be considered by growers of any other commodity with pests that can potentially be controlled biologically. Finally, further research is urgently needed to assist growers in implementing effective biological control and understanding the impact of individual pesticides on natural enemies.

Sustainability is often said to be composed of the "three 'E's", which can be defined loosely as environment, economy, and equality. This project attempted to address the first two, with results that should be useful to growers, farm advisors, policy makers, and other stakeholders in identifying the best methods of achieving a long-run sustainable solution which reduces the impact on water quality while preserving economic viability. Although reality is much more complex than the scenarios examined here, these results may offer insight into which growers are most likely to benefit from lowering water quality impact via the use of alternative products, if biological control can be successfully implemented to reduce secondary pest outbreak costs. The result are promising for encouraging the adoption of low impact pesticides, as can be seen in the following closing remark: averaging annual totals over the 5 year time span, we found that if all 43% of the PSs with potential for savings were replaced by their APS_{BIO}s, these growers could have saved an average of \$128 per hectare per year, and conventional pesticide use could have been reduced by 25,686 kg of organophosphate, 13,170 kg of miticide, and 248 kg of pyrethroid active ingredients, totaling an annual reduction of 39,105 kg of conventional active ingredients over 7749 hectares (5 kg/ha), thus contributing to both economic and environmental long-run sustainability.

Acknowledgements

The authors gratefully acknowledge the financial support of the California Department of Food and Agriculture, Agreement No. SCI7008, and the State Water Resource Control Board, Agreement No. 04-318-555-0. In addition, we would like to thank Richard DeMoura for his help in acquiring data.

Appendix A. Definitions of acronyms and select variables

Acronyms/terms	Definition
μl/l	Microliter per liter (≈1 part per million)
AI	Total kilograms of the dominant active ingredient of a pesticide product used in a PS or APS under varying scenarios
ALT	Total cost in US dollars per hectare of any alternative products in the PS
Alternatives	Pesticide group comprised of all PSs that included an alternative product
APS(s)	Alternative pest management system(s)

(continued on next page)

Appendix A (*continued*)

Acronyms/terms	Definition
BIO	Subscript indicating an assumption that naturally occurring biological control was an effective replacement of aphicide and miticide in the APS
BMP(s)	Best management practice(s)
Combination	Pesticide group comprised of all PSs that included both an organophosphate and a pyrethroid
COST	Total cost in US dollars per hectare of the PS or APS under varying scenarios
$COST_{wtdDIFF}$	Difference in cost between PS and APS under varying scenarios
EIQ	Environmental Impact Quotient scores derived from the EIQ model for PSs and APSs under varying scenarios (Kovach et al., 1992)
$EIQ_{wtdDIFF}$	Difference in EIQ score between PS and APS under varying scenarios
H	Survey-based weight representing APS's that treated for high codling moth pressure with pheromone plus methoxyfenozide, under assumption that biological control effectively replaced the need for aphicide or miticide
HN	Survey-based weight representing APS's that treated for high codling moth pressure with pheromone plus methoxyfenozide, and did not treat for aphid
HY	Survey-based weight representing APS's that treated for high codling moth pressure with pheromone plus methoxyfenozide, and treated for aphid with acetamiprid
IGR	Insect growth regulator
INDEX	Water quality index for the dominant active ingredient of a pesticide product, available online at the EIQ model website (Kovach et al., 2007)
L	Survey-based weight representing APS's that treated for low/moderate codling moth pressure with pheromone alone, under assumption that biological control effectively replaced the need for aphicide or miticide
LC_{50}	Lethal concentration: the concentration of the chemical that kills 50% of the test subjects in a given amount of time
LN	Survey-based weight representing APS's that treated for low/moderate codling moth pressure with pheromone alone, and did not treat for aphid
LY	Survey-based weight representing APS's that treated for low/moderate codling moth pressure with pheromone alone, and treated for aphid with acetamiprid

Appendix A (*continued*)

Acronyms/terms	Definition
mg/l	Milligram per liter (≈1 part per million)
MITE	Total cost in US dollars per hectare of all miticides in the PS
Miticides	Pesticide group comprised of all PSs that included a miticide
NOBIO	Number of pests targeted by a PS without potential to be successfully controlled biologically
OP	Total cost in US dollars per hectare of all organophosphates used in the PS
Organophosphates	Pesticide group comprised of all PSs that included an organophosphate
PRD	Total amount of a pesticide product used in a PS or APS under varying scenarios
PRICE	Price in US dollars per amount of pesticide product
PS(s)	Pest management system(s)
PUR	California Department of Pesticide Regulation's Pesticide Use Reports
PYR	Total cost in US dollars per hectare of all pyrethroids used in the PS
Pyrethroids	Pesticide group comprised of all PSs that included a pyrethroid
SPRYR	Total number of sprayer applications for the PS or APS under varying scenarios
Tradeoff	A cost increase resulting from switching from a PS to an APS to lower EIQ score
TRT	Total hectares treated by the PS
Π	Profit per hectare of PS or APS under varying scenarios

References

Agnello, A.M., Reissig, W.H., Kovach, J., Nyrop, J.P., 2003. Integrated apple pest management in New York State using predatory mites and selective pesticides. Agriculture, Ecosystems, and Environment 94, 183–195.

ANR, 2003. In: Integrated Pest Management for Walnuts, third ed.. Publication 3270 Regents of the University of California, Division of Agriculture and Natural Resources.

Bacey, J., Starner, K., Spurlock, F., 2004. The Occurrence and Concentration of Esfenvalerate and Permethrin in Water Sediment in the Sacramento and San Joaquin watersheds, EH04-01. Department of Pesticide Regulation, California Environmental Protection Agency.

Badenes-Perez, F.R., Shelton, A.M., 2006. Pest management and other agricultural practices among farmers growing cruciferous vegetables in the Central and Western highlands of Kenya and the Western Himalayas of India. International Journal of Pest Management 52, 303–315.

Brimner, T.A., Gallivan, G.J., Stephenson, G.R., 2005. Influence of herbicide-resistant canola on the environmental impact of weed management. Pest Management Science 61, 47–52.

Brookes, G., Barfoot, P., 2005. GM crops: the global economic and environmental impact – the first 9 years 1996–2004. AgBioForum 8, 187–196.

Buchner, R.P., Edstrom, J.P., Hasey, J.K., Krueger, W.H., Olson, W.H., Reil, W.O., Klonsky, K.M., De Moura, R.L., 2002. Sample Costs to Establish a Walnut Orchard and Produce Walnuts, Sacramento Valley, Sprinkler Irrigated. University of California, Cooperative Extension.

Bues, R., Bussieres, P., Dadomo, M., Dumas, Y., Garcia-Pomar, M.I., Lyannaz, J.P., 2004. Assessing the environmental impacts of pesticides used on processing tomato crops. Agriculture, Ecosystems, and the Environment 102, 155–162.

CASS, 2008. California Agricultural Statistics Service. 2007 California Walnut Acreage Report.

CDFA, 2007. Agricultural Statistical Review 2006 Overview, in California Agricultural Resource Directory, 2007, California. Department of Food and Agriculture.

CDPR, 2005. Study 229, Continuing Assessment of Pyrethroid Contamination of Surface Waters and Bed Sediments in High Pyrethroid-use Regions of California. Department of Pesticide Regulation, Sacramento, California.
CDPR, 2008. Pesticide Use Reports Database (PUR). California Department of Pesticide Regulation. <http://calpip.cdpr.ca.gov/cfdocs/calpip/prod/infodocs/aboutpur.cfm>.
CIMIS, 2008. California Irrigation Management Information System. <http://www.cimis.water.ca.gov/cimis/data.jsp>.
CTIC, 2006. Getting Paid for Stewardship: An Agricultural Community Water Quality Trading Guide. Conservation Technology Information Center. <http://www.conservationinformation.org/images/GPfS_FINAL.pdf>.
Coates, W.W., Van Steenwyk, R., Nomoto, R.M., 2001. Evaluations of Insecticides for Codling Moth Control in Walnuts-2000. California Walnut Marketing Board Research Reports 2000. Sacramento, CA. pp. 257–268.
Cross, P., Edwards-Jones, G., 2006. Variation in pesticide hazard from vegetable production in Great Britain from 1991 to 2003. Pest Management Science 62, 1058–1064.
Diamond, 2008. Diamond Foods 2008 Harvest Grower Guidelines for Delivery, Grading, and Payment. <http://www.diamondfoods.com/docs/growers/Harvest-Guide-2008.pdf>.
Edwards-Jones, G., Howells, O., 2001. The origin and hazard of inputs to crop protection in organic farming systems: are they sustainable? Agricultural Systems 67, 31–47.
EPA, 1997. Federal Register Environmental Documents, Raw and Processed Food Schedule for Pesticide Tolerance Reassessment. <http://www.epa.gov/fedrgstr/EPA-PEST/1997/August/Day-04/p20560.htm>.
EPA, 2006. 2006 Clean Water Act Section 303(d) List of Water Quality Limited Segments, California Environmental Protection Agency, State Water Resources Control Board. <http://www.swrcb.ca.gov/tmdl/303d_lists2006.html>.
EPA, 2007a. Biopesticide Active Ingredients and Products Containing Them. <http://www.epa.gov/pesticides/biopesticides/product_lists/bppd_products_by_AI.pdf>.
EPA, 2007b. Reduced Risk/Organophosphate Alternative Decisions for Conventional Pesticides, Office of Pesticide Programs. <http://www.epa.gov/opprd001/workplan/completionsportrait.pdf>.
FOOTPRINT, 2008. The FOOTPRINT Pesticide Properties Database. Database collated by the University of Hertfordshire as Part of the EU-funded FOOTPRINT Project (FP6-SSP-022704). <http://www.eu-footprint.org/ppdb.html>.
FWS, 2009. Partners for Fish and Wildlife Program. US Fish and Wildlife Service. <http://www.fws.gov/partners/>.
Gallivan, G.J., Surgeoner, G.A., Kovach, J., 2001. Pesticide risk reduction on crops in the Province of Ontario. Journal of Environmental Quality 30, 798–813.
Grafton-Cardwell, E.E., Godfrey, L.D., Chaney, W.E., Bentley, W.J., 2005. Various novel insecticides are less toxic to humans, more specific to key pests. California Agriculture 59, 29–34.
Grant, J.A., Kelley, K.M., Caprile, J.L., Klonsky, K.M., DeMoura, R.L., 2007. University of California Cooperative Extension 2007 Sample Costs to Establish a Walnut Orchard and Produce Walnuts, San Joaquin Valley North, Late Leafing, Lateral Bearing, Micro-sprinkler Irrigation, WN-VN-07.
JMP, 2009. JMP, Version 8. SAS Institute Inc., Cary, NC, 1989–2009.
Kenaga, E.E., 1978. Test organisms and methods useful for early assessment of acute toxicity of chemicals. Environmental Science and Technology 12, 1322–1329.
Kleter, G.A., Bhula, R., Bodnaruk, K., Carazo, E., Felsot, A.S., Harris, C.A., Katayama, A., Kuiper, H.A., Racke, K.D., Rubin, B., Shevah, Y., Stephenson, G.R., Tanaka, K., Unsworth, J., Wauchope, R.D., Wong, S., 2007. Review: altered pesticide use on transgenic crops and the associated general impact from an environmental perspective. Pest Management Science 63, 1107–1115.
Kovach, J., Petzoldt, C., Degni, J., Tette, J., 1992. A method to measure the environmental impact of pesticides. New York's Food and Life Sciences Bulletin 139, 1–8.
Kovach, J., Petzoldt, C., Degni, J., Tette, J., 2007. A Method to Measure the Environmental Impact of Pesticides, Table 2, List of Pesticides. <http://nysipm.cornell.edu/publications/eiq/files/EIQ_values07.pdf>.
Lichtenberg, E., Zilberman, D., 1986. The econometrics of damage control: why specification matters. American Journal of Agricultural Economics 68, 261–273.
Maki, A.W., 1979. Correlations between daphnia magna and fathead minnow (*Pimephales promelas*) chronic toxicity values for several classes of test substances. Journal of the Fisheries Research Board of Canada 36, 411–421.
Norwood, F.B., Marra, M.C., 2003. Pesticide productivity: of bugs and biases. Journal of Agricultural and Resource Economics 28, 596–610.
NRCS, 2009. Programs, Natural Resource Conservation Service, USDA. <http://www.nrcs.usda.gov/programs/CRP/>.
OECD, 2002. Guidance for the Registration Requirements for Pheromones and Other Semiochemicals used for Arthropod Pest Control, ENV/JM/MONO(2001)12. Organization for Economic Co-operation and Development.
OMRI, 2008. Organic Materials Review Institute. OMRI Products List, 2008. <http://www.omri.org/index.html>.
Oros, D.R., Werner, I., 2005. Pyrethroid Insecticides: An Analysis of Use Patterns, Distributions, Potential Toxicity and Fate in the Sacramento–San Joaquin Delta and Central Valley. White Paper for the Interagency Ecological Program, SFEI Contribution 415, San Francisco Estuary Institute, Oakland, CA.
Pickel, C., Grant, J.A., Welter, S.C., Buchner, R.P., Goldman Smith, S., 2007. Using Aerosol Pheromone "Puffers" for Area-wide Suppression of Codling Moth in Walnuts: Year 2 and Demonstration of Aerially Applied Pheromone Laminate Flakes, California Walnut Marketing Board Research Reports 2006. pp. 137–148.
PMRA, 1994. Isomate-C (Codling Moth Pheromone) Decision Document E94-01, Interdepartmental Executive Committee on Pest Management. Pest Management Regulatory Agency, Canada.
Prischmann, D.A., James, D.G., Wright, L.C., Teneyck, R.D., Snyder, W.E., 2005. Effects of chlorpyrifos and sulfur on spider mites (Acari: Tetranychidae) and their natural enemies. Biological Control 33, 324–334.
Smith, D.T., Harris, M.K., Liu, T.X., 2002. Adoption of pest management practices by vegetable growers: a case study. American Entomology 48, 236–242.
Schwankl, L.J., Hanson, B.R., Prichard, T.L., 2007. Reducing Runoff from Irrigated Lands: Causes and Management of Runoff From Surface Irrigation in Orchards. The Regents of the University of California, Division of Agriculture and Natural Resources, Publication 8214.
UC-IPM, 2008. Online Statewide Integrated Pest Management Program. UC Pest Management Guidelines; How to Manage Pests: Walnut. <http://www.ipm.ucdavis.edu/PMG/selectnewpest.walnuts.html>.
Van Steenwyk, R.A., Coates, W.W., Nomoto, R.M., Zolbrod, S.K., 2005a. Codling moth control in walnuts, 2004. Arthropod Management Tests 30, D13.
Van Steenwyk, R.A., Zolbrod, S.K., Nomoto, R.M., Fernandez, T.K., 2005b. Control of walnut husk fly using reduced risk products. Arthropod Management Tests 30, D13.
Weston, D.P., You, J., Lydy, M.J., 2004. Distribution and toxicity of sediment-associated pesticides in agriculture-dominated water bodies of California's Central Valley. Environmental Science and Technology 38, 2752–2759.
Wilhoit, L., 2002. Pesticide Use Report Loading and Error-Handling Processes. Department of Pesticide Regulation. PM 02-01.
Zalom, F.G., Stimmann, M.W., Arndt, T.S., Walsh, D.B., Pickel, C., Krueger, W.H., 2001. Analysis of permethrin (cis- and trans-isomers) and esfenvalerate on almond twigs and effects of residues on the predator mite *Galendromus occidentalis* (Acari: Phytoseiidae). Environmental Entomology 30, 70–75.