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Title: Economic analysis of revenue losses and control costs associated with the spotted wing drosophila (*Drosophila suzukii* (Matsumura)) in the California raspberry industry

Running Title: Economic analysis of spotted wing drosophila in California raspberries

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Abstract

BACKGROUND: The spotted wing drosophila (SWD), *Drosophila suzukii* (Matsumura), is an invasive vinegar fly with a preference for infesting commercially viable berries and stone fruits. SWD infestations can reduce yields significantly, necessitating additional management activities. This analysis estimates economic losses in the California raspberry industry resulting from the SWD invasion.

RESULTS: California raspberry producers experienced considerable revenue losses and management costs in the first years following SWD's invasion of North America. Conventional producers have since developed effective chemical management programs, virtually eliminating revenue losses due to SWD and reducing the cost of management to that of purchasing and applying insecticides more often. Organic raspberry producers, who do not have access to the same chemical controls, continue to confront substantial SWD-related revenue losses. These losses can be mitigated only by applying expensive insecticides registered for organic use and by performing labor-intensive field sanitation.

CONCLUSION: SWD's invasion into North America has caused extensive crop losses to berry and cherry crops in California and elsewhere. Agricultural producers and researchers have responded quickly to this pest by developing management programs that significantly reduce revenue losses. Economic losses are expected to continue to fall as producers learn to manage SWD more efficiently and as new control tactics become available.

1 INTRODUCTION

Drosophila suzukii (Matsumura) (Diptera: Drosophilidae), also known as the spotted wing drosophila (SWD), is a vinegar fly originating from Southeast Asia. SWD was first detected in North America in August 2008 in Santa Cruz County, California, where it was observed infesting strawberries and caneberries.[1,2] In 2009, SWD was detected in Washington, Oregon, and Florida. By 2010, SWD was detected in Utah, Mississippi, North Carolina, South Carolina, Wisconsin, and Michigan in the United States, and Alberta, Manitoba, Ontario, and Quebec in Canada.[3] Recent trapping indicates that SWD can be found in virtually any region of North America where host fruit are available. A coincidental invasion of SWD with a genetically distinct population has also been observed in Europe, with initial detections in both Spain and Italy in 2008, followed by its spread throughout the continent.[2,4,5]

In North America, SWD is primarily a pest of berries and cherries. In Europe, it is reported to also damage a number of stone fruits and grapes. Unlike native vinegar flies in North America and Europe, female SWD possess a serrated ovipositor that can pierce the skin of healthy, soft-skinned fruits to lay eggs. These eggs quickly develop into larvae, which consume the fruit and render it unmarketable. The only other *Drosophila* species known to oviposit in sound, marketable fruit is *Drosophila pulchrella* Tan. This species is native to Japan.[1] Growers have attempted to mitigate crop damage risk by applying additional insecticide, harvesting more frequently, performing field sanitation, and implementing trapping programs to detect SWD populations. These management practices are costly and many growers still face significant yield losses from SWD infestations.

We examine the economic impact of SWD infestations in the California raspberry industry. Raspberry producers are perhaps the most affected by SWD's invasion among

California commodities, although producers of blueberries and cherries have experienced substantial losses too. Strawberry producers have experienced lower damage rates and primarily on the lower-value fruit produced for processing. SWD-related losses in these industries vary by year and crop depending on management practices, weather conditions, time of the year, and geographic location. A primary motivation for focusing on the California raspberry industry is that California accounts for the majority of raspberry production in the U.S. and the raspberry industry accounts for the majority of economic losses due to SWD among berry crops.[6] A second motivation is the magnitude of change in pest management practices; few of the SWD control practices used by raspberry producers were needed to prevent injury from other pests prior to its establishment.

Economic losses in the California raspberry industry include the cost of managing SWD and the value of the fruit lost due to SWD infestations despite management efforts. First, we compute the cost of the chemical management programs and the labor-intensive sanitation practices implemented to mitigate SWD-related yield losses. Second, we calculate the industry-level yield losses due to infestation. These components form an estimate of the full economic cost of SWD's invasion into California raspberry production.

1.1 The California raspberry industry

Raspberry production is a valuable component of California's agricultural industry. In 2013, raspberries were estimated to be the twenty-seventh largest crop in California by value of production. California accounted for 74% of all raspberry production in the United States.[7] The United States is the third largest producer of raspberries in the world, producing 91,300 tonnes, after the Russian Federation and Poland, which produce 143,000 and 121,040 tonnes, respectively.[8] Across all counties, California's raspberry production was worth an estimated $239 million according to the United States Department of Agriculture's (USDA) National Agricultural Statistics Service (NASS), and $437 million ($462 million in 2014) according to California County Agricultural Commissioners' Reports.[7,9-12] The difference in these estimates reflects that the NASS data report cash receipts to producers while the Agricultural Commissioners' Reports estimate the total value of production. Figures 1, 2, 3, and 4 plot California raspberry hectares, production, yield per hectare, price per kilogram, and the total cash receipts between 2004 and 2013.[7] Note that raspberry hectares multiplied by yield per hectare is equivalent to production, and production multiplied by price per kilogram is equivalent to total cash receipts.

Four counties account for virtually all commercial raspberry production in California: Ventura, Santa Cruz, Santa Barbara, and Monterey.[7] In 2014, Ventura County produced approximately 52% of California's raspberry crop by value, $241 million, on 1,873 hectares. Raspberries are the third most valuable crop in Ventura County.[9] Santa Cruz County produced approximately 28% of California's raspberry crop by value, $131 million, on 979 hectares. Raspberries are the second most valuable crop in Santa Cruz County.[10] Santa Barbara County produced approximately 10% of California's raspberry crop by value, $45.2 million, on 591 hectares. Raspberries are the ninth most valuable crop in Santa Barbara County.[11] Monterey County produced approximately 10% of California's raspberry crop by value, $45 million, on 316 hectares. Raspberries are the sixteenth most valuable crop in Monterey County.[12] Table 1 summarizes California raspberry production by county.[9-12] Counties are listed from north to south along the Pacific Coast. Figure 5 identifies these berry-producing regions with a stylized map of California.

Most commercial raspberry plantings in California have had an 18-month lifespan. The crop is planted in the winter and then harvested twice, first in the fall following planting and then in the subsequent summer. Both harvest seasons last approximately three months, with crews harvesting fruit every three days on average. Variations in harvest frequency depend on yields and pest management activities. Yields are low at the beginning and end of a harvest season, and peak near the middle of a season. Pesticide applications may require an interval of time, depending on the particular pesticide, before normal harvesting activities can resume. This period is known as the pre-harvest interval (PHI), and it is determined by the U.S. Environmental Protection Agency. Occasionally, low yields are realized during the harvest season due to crop damage resulting from weather, pest activity, or other external factors. The summer harvest is typically larger than the fall harvest.[13]

Organically produced raspberries represent a significant share of total California raspberry production. In 2008 and 2011, California's organic raspberry production was valued at $11.4 million and $8.98 million, respectively, according to the USDA-NASS.[14] In 2012, 408 hectares of California raspberries were organically managed according to the University of California Agricultural Issues Center.[15] Raspberry prices vary throughout the year, but on average organic raspberries are sold at a price premium. In 2015, the national average retail price of organic raspberries over the entire year was $3.52 per six ounce (170.1 g) tray according to the USDA Agricultural Marketing Service. The average retail price of conventional raspberries over the same period was $2.55 per tray. The average California terminal market prices for organic and conventional raspberries were $3.29 and $1.97 per tray, respectively.[16]

California raspberries are a major export crop. In 2013, the combined category of raspberry, blackberry, mulberry, and loganberry exports was the twentieth largest export crop category by value in California. Raspberries account for the majority of the production volume and the total value of this category. This California export category was valued at $157 million, and accounted for approximately 85% of total US fresh and processed raspberry, blackberry, mulberry, and loganberry exports. 84% of these exports are received by Canada, 6% by Japan, and 5% by the European Union.[17]

1.2 Previous research

The presence of SWD has clearly increased production costs and caused yield losses for California raspberry producers through a variety of channels. Three previous studies have attempted to quantify the economic cost of the SWD invasion.[1,6,18] However, these studies occurred within one or two years of the first SWD infestations in North America when information on the pest was still sparse and management techniques were rapidly evolving. We can improve on these original estimates now that much more is known about SWD biology, risks, and management. We briefly review these original studies before establishing new estimates of the economic cost of SWD in the California raspberry industry.

Walsh *et al.* (2011)[1] and Bolda *et al.* (2010)[6] are the first studies to estimate the economic cost of SWD. These studies utilize yield loss estimates and observations for strawberries, blueberries, raspberries, blackberries, and cherries in California, Oregon, and Washington in conjunction with production data to calculate revenue loss estimates for each state and crop pairing. Walsh *et al.*[1] assume a yield loss of 20% for all the listed crops in these states. As a result, the study estimates a total of $511 million in potential damages annually due to SWD. Bolda *et al.*[6] continue the analysis by assuming the maximum reported yield losses of 40% for blueberries, 50% for blackberries and raspberries, 33% for cherries, and 20% for processing strawberries. The study concludes that potential revenue losses across these states and crops could be as large as $421.5 million given current prices.[6]

Goodhue *et al.* (2011)[18] refine these estimates of lost revenue for the California raspberry and strawberry industries by including potential price responses into their estimates. This additional assumption reflects that as the production of raspberries and strawberries decreases, the prices of these products may increase in response. The interaction between production and price is quantified with the inverse own-price elasticity of demand for each crop. The elasticity predicts the percentage change in price of a good in response to a 1% increase (or decrease) in quantity demanded. Drawing upon elasticity estimates established in prior studies, the authors conclude that SWD-induced yield losses could decrease California raspberry and processed strawberry revenues by up to 37% and 20%, respectively. The authors also evaluate the cost of different SWD-targeting insecticide applications and the cost of a specific conventional raspberry pest control program in California's Central Coast region. The insecticide material and application costs are estimated to be $825.33 per hectare. However, these chemical applications may also provide incidental control of other pests. This implies that the estimate represents an upper bound of the potential chemical control costs associated with SWD.[18]

The revenue loss and management cost estimates in these prior studies can be substantially improved using current information about SWD-induced yield losses and management practices. Fruit losses due to SWD and SWD management costs have decreased over time as researchers and producers have developed and implemented better techniques for reducing crop losses. We can also more accurately estimate historic yield losses now that more is known about SWD biology, its spread, and the efficacy of different management techniques.

Lastly, we can now incorporate increases in labor costs into these SWD management cost estimates.

2 EXPERIMENTAL METHODS AND RESULTS

This analysis has two components. First, we utilize recent estimates of SWD-induced yield losses in the California raspberry industry to calculate industry-level revenue losses for both organic and conventional raspberry producers. Second, we revise prior estimates of SWD management costs to reflect the cost of modern organic and conventional chemical management programs and the increased labor costs resulting from the presence of SWD.

2.1 Revenue losses

Prior estimates of SWD-induced revenue losses were based on the maximum observed yield losses in different industries where SWD infestations occurred. These estimates provide information about SWD's damage potential, but do not yield an accurate estimate of actual SWD crop damage. Actual crop damage is useful for estimating revenue losses due to SWD and will differ by year and production style. This analysis incorporates field trial results and expert opinions to estimate SWD-induced revenue losses for the California raspberry industry.

SWD infestations directly reduce raspberry yields in two ways. First, fruit infested by SWD decay more quickly. These yield losses are difficult to attribute to SWD because the initial infestation is difficult to detect, and the accelerated decay has a similar appearance to decay caused by fungal diseases, bacteria, and yeasts. Second, raspberry shippers that detect SWD infestations may reject the entire delivery from the grower. Fresh fruit are held to rigorous quality standards. The risk of rejection of an entire delivery incentivizes growers to eliminate all visible defects in harvested fruit.

SWD infestations are more prevalent late in the year as the population grows until winter weather reduces the population.[19] Further, raspberry production is fairly concentrated geographically and the leftover, overripe fruit from nearby fields' summer harvest acts as a breeding ground for SWD. SWD infestations are also more prevalent in fruit destined for the processing market, where the price is lower than in the fresh market. Fruit intended for processing are harvested later in the season, tend to be riper because they are harvested less frequently, and receive less frequent pesticide treatments.

SWD damage rates could change significantly in the future due to pesticide resistance development and the introduction of new SWD management practices, including introducing biological control agents. Recent studies in the US and Europe found that indigenous parasitoids had limited effect on SWD populations.[20-22] However, in Asia, where SWD originates, several endemic parasitoids attack and develop from SWD.[23-25]

We begin by examining SWD-induced yield losses in California's conventional raspberry industry. The original reports of SWD damage in the raspberry industry indicated that as much as 50% of production could be lost if SWD was left unmanaged.[6,18] Yield losses of this magnitude occurred as raspberry producers first learned how to manage SWD, but are now uncommon due to implementation of extensive academic research and industry experience. According to private communications with conventional raspberry producers, they have managed to reduce SWD-induced yield losses to less than 3% of production. In recently published reports, conventional raspberry producers that employ effective chemical management programs face virtually no yield losses due to SWD.[18,26] This substantial reduction in yield losses is primarily attributable to two factors. First, conventional raspberry producers have access to cheap and effective chemical management options.[27] Second, these producers are harvesting their crop more frequently in order to reduce the amount of time raspberries are susceptible to infestation.

These observations of actual SWD-induced yield losses are consistent with field trial observations as well. Entomologists Kelly Hamby and Frank Zalom monitored traps and evaluated fruit samples for damage between October 2010 and December 2012 in both organically- and conventionally-managed raspberry sites. Analyzing the 40-fruit samples collected from these fields resulted in estimated yield loss observations for raspberry producers employing standard management practices at the time. SWD-induced yield losses for conventional producers in the study were estimated to be approximately 10% of production in 2011 and less than 1% in 2012.[26] These estimated yield losses are consistent with those observed by De Ros *et al.* (2015)[28] in Italy between 2011 and 2013. De Ros *et al.* estimated raspberry losses of 11.5% prior to i and 3.24% after the implementation of an integrated strategy.

The yield losses observed in the UC Davis study were concentrated in the fall harvest.[26] The summer harvest is hypothesized to experience less SWD pressure because the population grows throughout the year until cold weather arrives and lack of host fruit in the winter significantly reduces population levels. SWD biology and infestation intensity is affected by climatic conditions and the availability of host fruit, implying that different climatic conditions and influences of neighboring crops could significantly impact SWD-related yield losses.[29-31]

On the other hand, organic raspberry producers still face significant SWD-induced yield losses. Private communications with raspberry producers indicate that these producers experience yield losses between 5% and 15% of production due to a lack of efficacious chemical treatments approved for organic use, and the efficacy and high cost of other labor-intensive SWD management practices. Once again, these field observations are consistent with the yield losses measured in field trials. SWD-induced yield losses for organic raspberry producers in the study were estimated to be approximately 12% of production in both 2011 and 2012.[26]

We calculate yearly estimates of industry-level revenue losses using these observed yield losses due to SWD and a procedure similar to Goodhue *et al.* (2011).[18] First, we assume an own-price elasticity of demand for raspberries of -1.66. This elasticity value is the value estimated for fresh raspberries by Sobekova, Thomsen, and Ahrendsen (2013).[32] Second, we assume that actual yield losses in the California raspberry industry correspond to the yield losses observed in the field trials. Specifically, we assume that SWD-induced yield losses between 2009 and 2011 correspond to the yield losses observed in 2011, and that losses after 2011 correspond to the yield losses observed in 2012. Raspberry production and price data are obtained from the U.S. Census of Agriculture and various National Agricultural Statistics Service (NASS) surveys.[14,33] Table 2 provides the resulting revenue loss estimates organized by production practice and year grouping.

California's conventional raspberry producers faced a total of $36.1 million in revenue losses due to SWD between 2009 and 2011. These estimated revenue losses are equivalent to 4.62% of realized revenues over the same period. After 2011, effective SWD management techniques in conventional production eliminated virtually all revenue losses. Revenue losses due to SWD between 2011 and 2014 are estimated to be $277 thousand, which is less than 1% of realized revenues over the same period. In total, California's conventional raspberry producers faced $36.4 million in revenue losses due to SWD between 2009 and 2014.

California's organic raspberry producers faced a total of $3.43 million in revenue losses due to SWD between 2009 and 2014. These estimated revenue losses are equivalent to 5.74% of realized revenues over the same period. Revenue losses of this magnitude are expected to continue in organic raspberry production until more effective chemical, cultural, or biological management programs are discovered. Furthermore, revenue losses incurred by organic raspberry producers could potentially increase dramatically if SWD populations develop greater resistance to the current, limited set of chemical controls approved for organic use.

2.2 Chemical management costs

SWD management is multifaceted. In addition to yield losses, managing SWD has significantly increased production costs for raspberry producers. Raspberry growers increase the number of insecticide applications and use additional labor to harvest their crop in response to SWD infestation pressure. These necessary insecticide applications require additional chemical purchases and access to sprayers and specialized equipment through custom application or purchase. Overuse of pesticides can lead to rejections of shipments if residues exceed legal tolerances for the chemicals; however, producers who adhere to mandatory label rates should, theoretically, never encounter this problem.

Conventional raspberry producers have access to a variety of insecticides that provide excellent control for SWD populations at present. Raspberry growers observed in the UC Davis study discussed earlier applied SWD-targeting insecticides four to six times for both the fall and spring harvests. The most commonly used insecticides for this purpose were spinetoram, zeta-cypermethrin, and malathion. Assuming these chemicals are applied at their maximum label rates and with generic purchase prices observed in 2015, the per hectare material costs of these insecticide applications are \$179.40, \$7.22, and \$29.78, respectively. Using a conventional raspberry grower observed in the UC Davis study as a point of reference, an example chemical management program included two applications of spinetoram and a combined application of zeta-cypermethrin and malathion in both the fall and spring harvest seasons. Each application is estimated to have labor and equipment costs of $61.78 per hectare.[13] In 2015, such a program would cost an estimated $581.14 per hectare in both the fall and spring harvests for a total cost of $1,161.28 per hectare for a single planting. This is consistent with the per hectare treatment program cost of $825.33 observed in Goodhue et al in 2011.[18]

Even though conventional raspberry producers have developed effective chemical management programs that virtually eliminate fruit losses due to SWD, organic producers still experience non-trivial yield losses due to more expensive and less effective insecticide options.[26] Most California organic raspberry producers used only two SWD-targeting insecticides, spinosad and pyrethrin, during the time of this study. Of these two insecticides, only the organic formulation of spinosad has efficacy comparable to conventional insecticides.[34,35] Spinosad applications are more expensive than conventional insecticides and organic growers are limited by its labeled use of two consecutive applications followed by rotation to a product containing another class of insecticide (such as pyrethrin) for resistance management. Pyrethrin has been shown to have a limited effect on SWD populations.[34,35] It is typically applied in conjunction with spinosad or other organic insecticides because it does not provide sufficient control on its own.

Assuming spinosad and pyrethrin are applied at their maximum label rates and with generic purchase prices observed in 2015, the per-hectare material costs of these insecticide applications are $200.60 and $119.13, respectively. In the UC Davis study, organic raspberry growers were observed applying these insecticides between five to nine times for each seasonal raspberry harvest. Using an organic raspberry grower observed in the UC Davis study as a point of reference, a typical chemical management program included five applications of pyrethrin in the fall, three of which were applied in conjunction with spinosad, and six applications of pyrethrin in the spring, two of which were applied in conjunction with spinosad. Assuming the stated per-hectare material, labor, and equipment costs, such a program would cost an estimated $1,506.35 per hectare in the fall and $1,486.66 per hectare in the spring for a total cost of $2,933.01 per hectare for a single planting.

It is important to note that even as these insecticide applications reduce SWD populations, they also provide control for other pests such as the light-brown apple moth, *Epiphyas postvittana* (Walker) (Lepidoptera: Tortricidae). As a result, it is difficult to attribute the entire cost of these chemical management programs strictly to the management of SWD. However, few insecticide sprays were applied to California raspberries before the SWD invasion, and the light-brown apple moth, another invasive insect, only impacts portions of the Santa Cruz and Monterey County raspberry production areas at present. The light-brown apple moth can also be effectively controlled more inexpensively with the organic microbial insecticide *Bacillus thuringiensis* Berliner. Therefore, we can infer that the majority of the observed insecticide applications included in this analysis were intended to control SWD populations.

2.3 Labor management costs

We also consider the additional labor costs associated with managing SWD in order to develop a comprehensive estimate of SWD management costs. Like many other horticultural products, raspberries are extremely labor-intensive to produce. Labor, the primary production cost, includes planting, pruning, weeding, spraying, hauling, cleanup, field sanitation, and harvesting.[13] SWD control programs necessitate labor-intensive management practices in addition to chemical applications. Three labor-intensive control activities are currently used to reduce SWD-related yield losses: increasing the frequency of harvests, performing field sanitation, and implementing trapping programs to detect the presence of SWD populations.[27] Further compounding these direct labor costs, the productivity of harvesting labor decreases as more frequent harvests and fruit losses due to SWD reduce the availability of marketable fruit to pick. Labor-intensive management activities are more intensely utilized by organic producers due to the lack of efficacious organic chemicals.

Increasing the frequency of raspberry harvests means that fruit is harvested sooner, thus reducing the availability of ripe fruit in the field. SWD primarily targets red fruit that is fully ripened or overripe.[36] While SWD also infest fruit before they ripen, this damage is less pervasive. Even if SWD infestations are present in less ripe fruit, the damage is less likely to be visible if the fruit is quickly harvested and cooled. Once fruit enters the cold chain, SWD development slows dramatically. As a result, a common practice among raspberry growers facing SWD damage has been to harvest a day sooner.[26] Prior to the SWD invasion, raspberries were typically harvested every two to six days depending on the time of the season.[13] Decreasing this interval to every one to five days implies a potential 20% to 100% increase in the frequency of harvests due to SWD, depending on the time of the season.

Labor-intensive field sanitation efforts, which include pickers removing fallen and damaged fruit, is another means of reducing the availability of fruit for SWD to infest. Fallen and damaged fruit are a breeding ground for SWD and other *Drosophila* species alike. Removal of such unmarketable fruit from the field eliminates one potential source of SWD population growth, though external SWD populations can still be a significant source of damage. Field sanitation is a recommended practice for all raspberry production even in the absence of SWD, but extensive field sanitation efforts are more likely to be observed with organic producers due to their greater damage rates and the costliness of such activities. Field sanitation is costly because pickers must be compensated. A common practice is to pay pickers a secondary, lower piece-rate for harvesting and disposing damaged fruit. Pickers performing field sanitation have been observed allocating as much as a quarter of their harvesting time to removing unmarketable fruit.[26] For example, Rogers, Burkness, and Hutchison (2016)[34] examined SWD infestations in Minnesota raspberries and found that the average percentage of unmarketable fruit in untreated open plots was 29%. SWD infestations were found in 81% of sampled berries in these untreated open plots. Similarly, De Ros *et al.* (2015)[28] observed Italian berry growers allocating approximately a labor-hour per hectare each harvest day for sanitation efforts intended to control SWD. Growers who don’t remove fallen and damaged fruit have been observed to sustain increased damage rates as well as a higher probability of rejection of the whole shipment.

A final labor-intensive management practice performed by many growers is the construction and maintenance of attractant-based traps. The materials required to produce these traps are inexpensive, but the construction and placement of the traps can be a labor-intensive activity.[28] Growers utilize these traps to detect the presence of significant SWD populations in the fields they manage. However, available traps and attractants are nonspecific and capture many species of vinegar flies. In general, fly captures are a weak predictor of fruit losses.[26,37,38] Producers often respond with more frequent insecticide applications and more intensive field sanitation when trap captures indicate the presence of large vinegar fly populations.

Overall, the primary benefit of trapping programs has been to alert producers to the presence of SWD in areas where SWD had never been detected before. Regional trapping programs implemented by SWD researchers have also provided a rough measure of adult SWD activity at a given time of the year. Sampling fruit directly provides a more accurate estimate of damage because virtually all fruit fly infestations in commercially viable California raspberries are SWD. However, direct sampling of fruit for infestations is time consuming for raspberry growers, who must transport their highly perishable product to a shipper within hours of a harvest.[6] It is also a *post facto* measure since the fruit infestation measured has already occurred, so control at that time is of no value.

In addition to growers implementing these labor-intensive SWD management practices, more frequent harvesting and fruit losses due to SWD limit how efficiently a grower can utilize labor. More frequent harvesting and fruit losses reduce fruit density in a field. Workers' harvesting productivity is negatively impacted when they must spend additional time searching for marketable fruit that is less densely available.[13,39] The harvest rate per raspberry picker can vary from one to five trays per hour depending on worker skill and fruit availability.[13] An experienced picker can harvest up to 2.5 times more quickly than a novice, and yield alone can cause worker productivity to vary by a factor of two.[39] SWD damage has the potential to reduce raspberry yields by up to 50% over a season and up to 100% in a specific harvest; therefore, it is clear that SWD damage can significantly affect workers' productivity.

Further compounding these labor-utilization issues, growers must offer a higher piece-rate when productivity is low in order to retain their labor force and increased variability in available yield for harvest makes it more difficult for managers to allocate labor appropriately. The market for raspberry pickers is highly competitive.[26] Workers who believe they can earn more money elsewhere, because less fruit is damaged, may leave during a harvest or not return for a subsequent harvest. The potential resulting labor shortage in fields with significant SWD damage could further exacerbate fruit losses due to SWD as unharvested fruit become overripe and act as a SWD breeding ground. Further, agricultural labor costs are also rising over time as the supply of labor from Mexico is shrinking due to improving economic conditions.[40]

It is difficult to observe these increased labor costs directly, but it is clear that they are not negligible. In 2015, a tray of 12 six ounce (170.1 g) clam shells of conventional raspberries sold at an average price of $15.98 per tray based on Salinas-Watsonville and Oxnard district shipping point prices.[16] According to a 2012 UC Davis study of raspberry production costs and returns, production costs were estimated to be $10 per tray of raspberries. Labor costs accounted for approximately half of these production costs, and the study did not report any SWD-targeting activities. The piece-rate alone averaged $4 per tray in a season.[13] If one were to assume, conservatively, that these additional labor costs associated with managing SWD increased total labor costs by as little as 2% and 4% for conventional and organic raspberry producers, respectively, then these activities would account for a 1% and 2% increase in total production costs. Thus, a 1% increase is production costs would reduce a conventional raspberry grower's profit margin by approximately 1.67%. If a similar cost structure is assumed for organic raspberry producers, then one would expect approximately a 3.34% reduction in profit margin resulting from the additional labor costs associated with managing SWD. Labor costs are assumed to increase by a greater percentage for organic producers because they are more reliant on labor-intensive SWD control methods.

3 DISCUSSION AND CONCLUSIONS

SWD's invasion into North America has significantly harmed the California raspberry industry. We examined revenue losses and management costs associated with this invasive pest. Using a combination of field trial data and expert observations, we calculated that SWD has accounted for approximately $39.8 million in revenue losses, equivalent to 2.19% of realized revenues, for the California raspberry industry between 2009 and 2014. Conventional producers accounted for $36.4 million of these losses, equivalent to 2.07% of their realized revenues. Organic producers accounted for $3.43 million of these losses, equivalent to 5.74% of their realized revenues. SWD management activities have also significantly increased production costs for raspberry growers. We calculated that the cost of chemical purchases increased annual per hectare production costs for conventional and organic producers by $1,161.28 and $2,933.01, respectively. We also calculated that the cost of labor-intensive SWD management activities decreased conventional and organic raspberry producers' profits by 1.67% and 3.34%, respectively. Even though the industry has managed to adapt to the pest, these revenue losses and management costs have significantly reduced the profitability of the commercial production of fresh raspberries.

Looking into the future, it is unclear whether SWD will remain a threat to California's raspberry producers. On one hand, the primary biological reason that SWD has become such an economically damaging pest in both North America and Europe following its invasion is the absence of an effective natural enemy. In Asia, where SWD originates, the presence of effective natural enemies greatly reduces damages associated with the pest. Thus, the introduction of an effective biological control agent could dramatically reduce these estimated losses in the future. On the other hand, California's raspberry producers rely heavily on chemical management options to reduce yield losses associated with SWD infestations. If SWD populations were to develop significant resistance to these chemicals over time or restrictions were placed on their use, then these estimated losses could increase dramatically.

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Table 1. California raspberry production by county

County	Production ($US millions) 2013	2014
Santa Cruz	152	131
Monterey	43.8	45.0
Santa Barbara	N/A	45.2
Ventura	196	241
Total	437[a]	462

[a] Alternate year used when production estimate not available

Table 2. Estimated average per year effects of SWD-induced yield losses in the California raspberry industry by production practice

Year	Base quantity (kg)[b]	Base Price ($US kg^{-1})[b]	Yield reduction (%)	Price change (%)	Quantity (kg)	Price ($US kg^{-1})	Estimated revenue losses ($)	Revenue change (%)
				Conventional				
2009	61,871,717	6.04	-9.68	5.82	55,882,534	6.39	$16,521,893	-4.42
2010	40,678,645	5.15	-9.68	5.82	36,740,952	5.45	$9,251,946	-4.42
2011	54,238,193	4.31	-9.68	5.82	48,987,936	4.56	$10,338,206	-4.42
2012	44,120,468	5.44	-0.07	0.04	44,089,142	5.45	$67,998	-0.03
2013	48,795,785	5.60	-0.07	0.04	48,761,140	5.60	$77,335	-0.03
2014	67,860,185	6.85	-0.07	0.04	67,812,004	6.86	$131,684	-0.03
				Organic				
2009	2,154,685	5.61	-11.5	6.92	1,906,896	6.00	$649,779	-5.38
2010	2,154,685	5.61	-11.5	6.92	1,906,896	6.00	$649,779	-5.38
2011	1,949,250	4.87	-11.5	6.92	1,725,087	5.20	$510,027	-5.38
2012	1,953,665	4.86	-11.7	7.04	1,725,087	5.20	$520,824	-5.48
2013	1,953,665	4.86	-11.7	7.04	1,725,087	5.20	$520,824	-5.48
2014	2,189,717	4.86	-11.7	7.04	1,933,520	5.20	$583,753	-5.48

[b] Note that the NASS production and price data are found in the “Quantity” and “Price” columns. “Base quantity” and “Base Price” are calculated by adding the estimated yield losses and price changes to the observed data.

Figure Legends

Figure 1. California harvested raspberry hectares, 2004-2013.

Values are statewide totals organized by crop year.

Figure 2. California raspberry production and yields, 2004-2013.

Values are statewide totals and averages organized by crop year.

Figure 3. California raspberry prices at first point of sale, 2004-2013.

Values are statewide cash receipt averages organized by crop year.

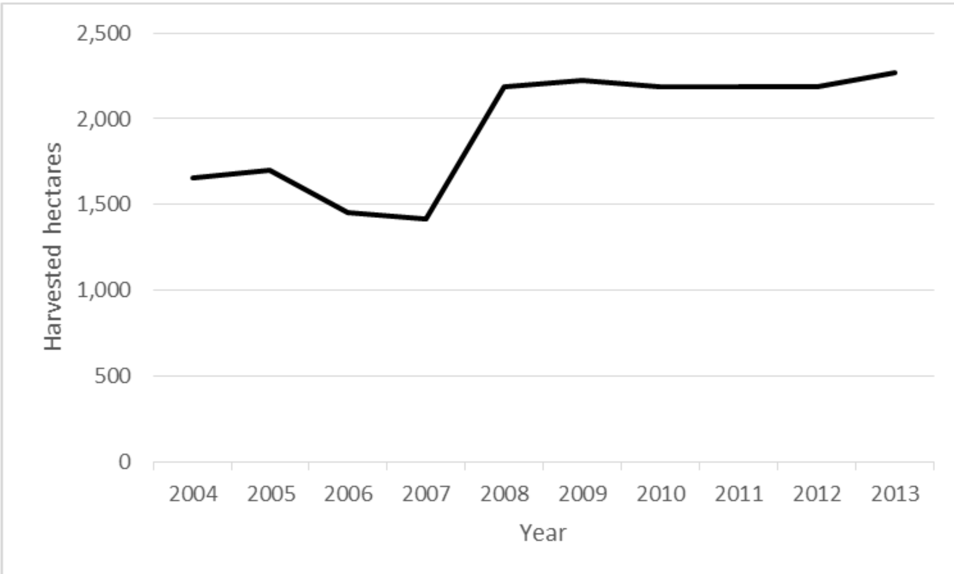
Figure 4. California raspberry production total value, 2004-2013.

Values are statewide cash receipt totals at first point of sale organized by crop year.

Figure 5. Stylized Map of California's Central Coast Highlighting Berry-producing Regions.

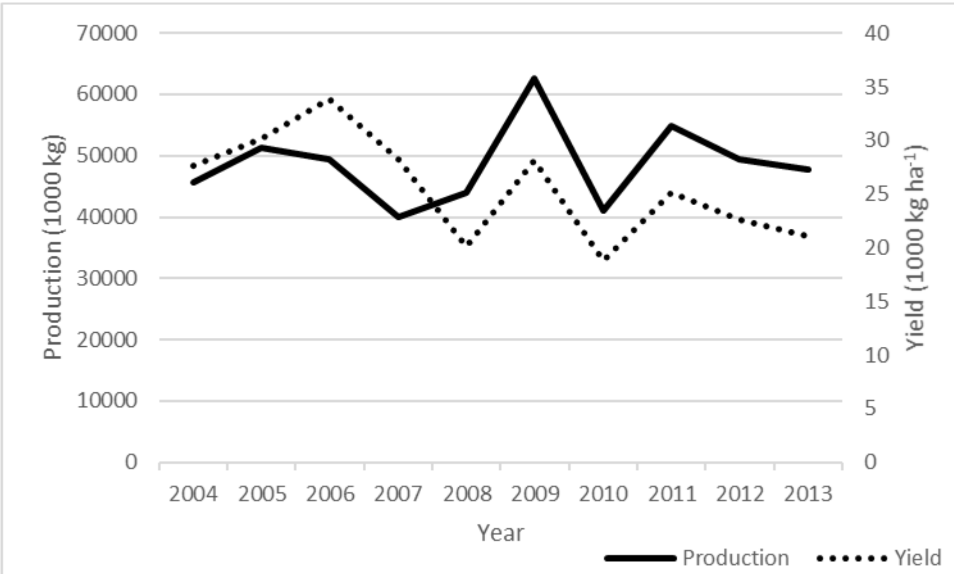
Arrows and circles identify the major berry-producing regions.

Figure 1. California harvested raspberry hectares, 2004-2013



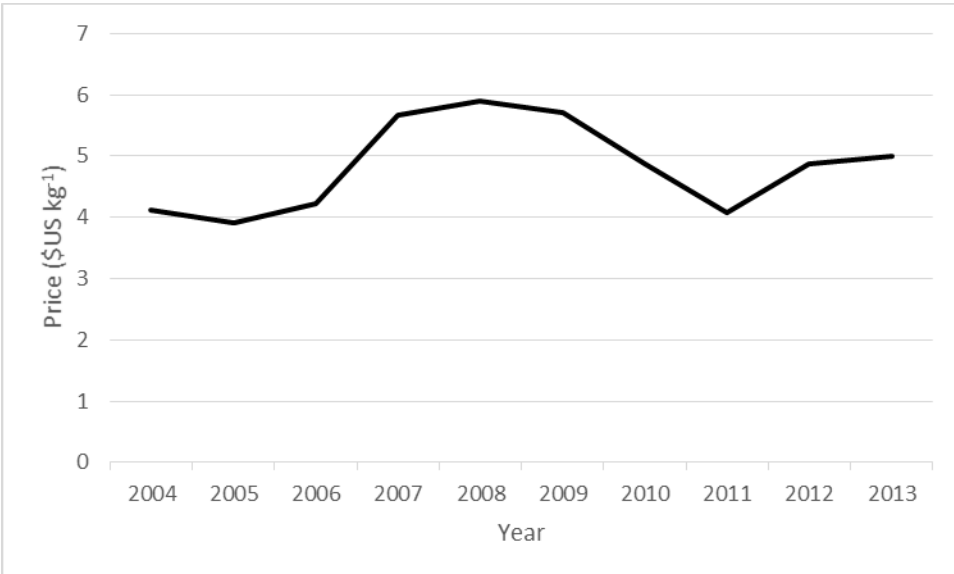
Values are statewide totals organized by crop year.

Figure 2. California raspberry production and yields, 2004-2013



Values are statewide totals and averages organized by crop year.

Figure 3. California raspberry prices at first point of sale, 2004-2013



Values are statewide cash receipt averages organized by crop year.

Figure 4. California raspberry production total value, 2004-2013

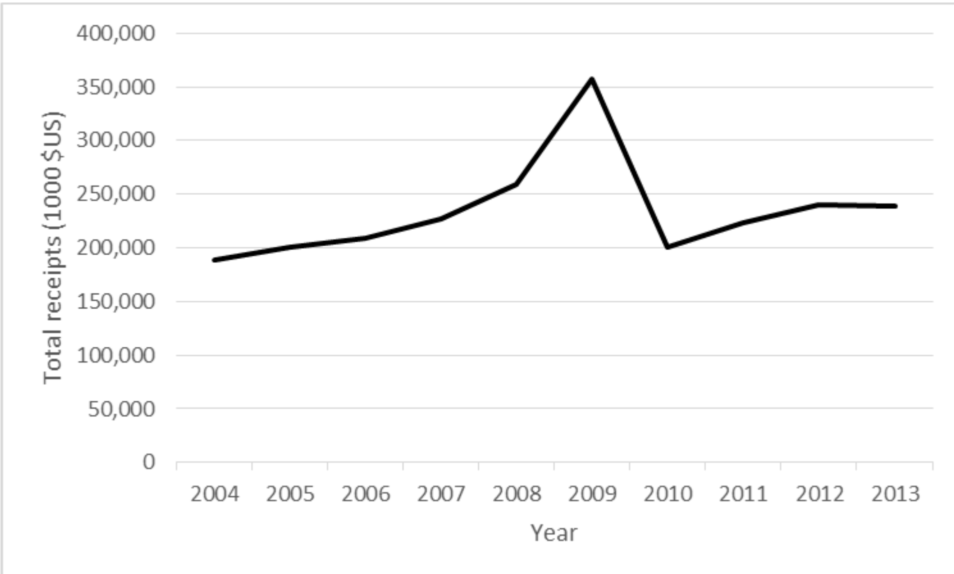


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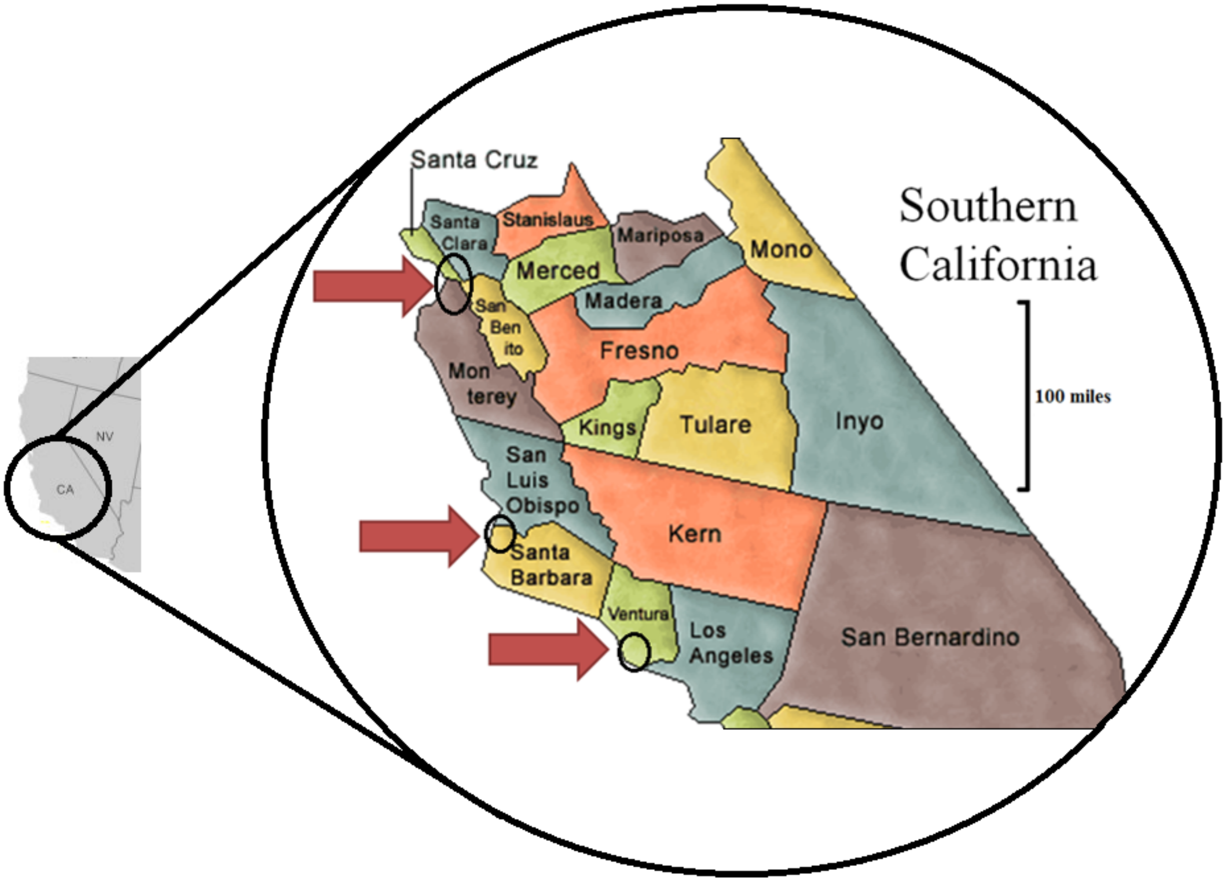
Figure 5. Stylized Map of California's Central Coast Highlighting Berry-producing Regions



Arrows and circles identify the major berry-producing regions.