Explaining Agricultural Labor Shortages with Unpredictable Product Losses: 
A Case Study of Spotted Wing Drosophila in California Raspberries

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Job Market Paper
November 2013

Abstract
California agricultural producers are reporting labor shortages, particularly for commodities that require considerable seasonal harvesting labor. I propose that these perceived labor shortages can be partially explained by producers misjudging market wages due to unpredictable product losses in piece-rate harvesting operations. Using a recent invasive vinegar fly infesting Central Coast raspberries as an empirical example, I model the effect of fruit losses, unobserved by managers, when compensation is tied to a piece-rate. I find that these losses cause producers to offer net earnings below a market rate, with greater losses causing more distorted wages. Rational, informed workers select growers offering the highest net earnings and avoid growers who substantially misjudge piece-rates, further compounding yield losses in fields with significant infestation. Direct fruit losses from the invasive are estimated to be 4.9% of production for conventional raspberry growers observed in a scientific study. Should these fruit losses reduce worker productivity, estimated yield losses increase to 6.0%, with harvesting labor costs increasing 12%. These results demonstrate that productivity-compensated agricultural workers have a significant monetary incentive to arbitrage between fields, explaining why some growers may have difficulty hiring sufficient harvesting labor.
**Introduction**

A standard assumption in economics is shortages should never occur in efficient, integrated markets. California agricultural labor markets have long been considered highly efficient and integrated, with workers observed moving between operations for even a minimal increase in net earnings. Nevertheless, California growers and media are reporting widespread agricultural labor shortages, particularly in industries reliant on seasonal harvesting labor (California Farm Bureau Federation 2012; O’Brien 2012; Schwartz 2013; Souza 2013; Wells 2012). Many of these growers claim that they can’t find enough labor to harvest their fields fully no matter what compensation they offer.

Parallel to these observations, recent economic research has observed a stagnating supply of undocumented labor from Mexico (Taylor et al. 2011; Taylor, Charlton, and Yúnez-Naude 2012). These studies explain increasing wages in agriculture, but fail to address why some growers perceive a shortage. Even if market wages are increasing in an industry, a producer should still be able to acquire sufficient harvesting labor by offering high enough net earnings. In theory, agricultural workers are willing to relocate for greater earnings, so why aren’t they appearing when a grower substantially increases her offered piece-rate?

I construct a theoretical model of agricultural labor markets operating on a piece-rate to offer a potential explanation for these perceived shortages when compensation is tied to productivity. The model emphasizes the role of unpredictable product losses, which are only observed by workers and not managers. In raspberry harvesting, for example, the worker is the one positioned to pick berries hidden by foliage or to ignore overripe berries. I hypothesize that if these unpredictable losses are large enough, growers will overestimate worker productivity and advertise net earnings below the market rate, thus perceiving a labor shortage as workers seek
more lucrative positions elsewhere. I confirm these theoretical findings using a recent invasive vinegar fly infesting raspberries, spotted wing drosophila (SWD), as a case study. I establish that the fruit losses introduced by SWD are significant and unpredictable using sampling data from a detailed scientific study. I then estimate the degree to which raspberry growers may misjudge a worker’s total earnings when setting a piece-rate because of SWD-related productivity decreases, and the resulting equilibrium market effects.

A critical assumption of the analysis is that there are factors determining a worker’s potential earnings which a manager cannot observe. In agricultural production, a field’s yield significantly affects a worker’s productivity. However, yield and productivity may not be completely known to a grower until after a harvest is complete. For commodities such as raspberries, yields may be very unpredictable for the multiple, frequent harvests occurring throughout the season due to variations in pest pressure. This unpredictability is especially characteristic of organic raspberry production, and perhaps a motivating reason for why organic raspberry growers primarily offer an hourly wage, as opposed to the piece-rate compensation that permeates conventional raspberry harvesting.

If a manager is unable to fully anticipate variation in fruit availability, she might perceive a labor shortage when conditions are such that productivity is significantly reduced. An uncompensated productivity loss causes workers’ realized compensation to fall, and may trigger workers to seek greater earnings at another operation. Workers are well-informed about their potential earnings at other locations. They share information via social networks and have easy access to farm labor contractors. A worker who makes less money than she anticipated may almost immediately move to another producer offering higher net earnings. Additionally, a
productivity loss implies that the remaining workers harvest fruit less quickly than originally anticipated by the manager.

This labor-allocation problem is easily generalized to other industries that compensate an employee based on productivity. Depending on the information available to managers and employees, there can often be a significant difference in expected earnings, especially when operating on a piece-rate or commission. For example, a waiter, dependent on tips, may anticipate different earnings than a manager assigning shifts and potentially quit when earnings are low. As another example, contributors to a project may anticipate the project’s failure, and thus seek reassignment. Whenever compensation is based on productivity, expectations about that productivity inform a worker’s choice of job.

**Theoretical Model**

Framing the analysis, I propose a theoretical model. This model describes a piece-rate labor market where a worker’s earnings are determined by a firm’s offered piece-rate, her skill, and the availability of fruit for picking. A firm’s profits are determined by the price of the product, the offered piece-rate, and the fruit available that harvest. I use the model to discuss how unpredictable product losses affect a firm’s offered piece-rates as well as its ability to hire enough labor. The model demonstrates that firms may overestimate yields, causing perceived labor shortages when workers choose to work for competitors offering greater net earnings.

A piece-rate incentivizes workers to harvest efficiently without the need for constant supervision, by rewarding each unit of production. Risk-neutral raspberry picker \(i\), operating on a standard piece-rate for firm \(f\), has the following profit-maximization problem:

\[
\text{(1) } \quad \max_{\pi_i} \pi_i = \sum_{f=1}^{F} r_f y_f l_{if} \\
\text{ s.t. } \quad \sum_{f=1}^{F} l_{if} \leq 1 \quad \text{and} \quad \sum_{i=1}^{I} l_{if} < L_f
\]
Workers allocate their time, \( l_f \), given the piece-rate, \( r_f \), and the yield parameter, \( y_f \), associated with each firm. A parameter for a field’s full yield is included because of the effect of fruit density on a worker’s productivity. Prior empirical research has demonstrated that harvesting labor productivity increases with a field’s available yield (Roka and Hyman 2012). A worker’s labor endowment is standardized to one for simplicity. A firm’s maximum production occurs at \( L_f \). Firms are assumed to be sufficiently large enough that a single worker cannot harvest all of a firm’s production. Differentiating and rearranging the maximization problem yields:

\[
(2) \quad 0 = r_f y_f
\]

The first-order condition is arranged with marginal cost on the left-hand side and marginal benefit on the right. Aided by information sharing via social and professional networks, workers select firms that offer the highest net earnings and fully expend their labor endowment. Workers consider more than a firm’s piece-rate when choosing where to work. They consider the available yield for picking at different firms. Within this setting, workers choose to work at firms with high yields and high piece-rates to maximize their net earnings.

Complementing the worker’s profit-maximization problem is the firm’s own profit-maximization problem, found in equation (3). Firms earn profit, \( p - r_f \), on each harvested fruit, \( q \). A firm’s production function is increasing in the piece-rate the firm offers and has a maximum at \( Q_f \). With this initial setup, there is no downward distortion in earnings from unpredictable yield losses.

\[
(3) \quad \max_{r_f} \pi_f = (p - r_f)q(r_f, y_f)
\]

subject to \( q(r_f, y_f) \leq Q(y_f) \)

Differentiating and rearranging the maximization problem yields:
Firms choose a piece-rate such that the gain in revenue from increasing wages, $p \cdot \Delta q$, is equal to the additional wages associated with the new production, $r \cdot \Delta q$, plus the increase in wages on all production, $q(r_f, y_f)$. Depending on parameter values and the functional form of the production function, there is a potential corner solution where firms harvest the maximum amount of fruit given their yield parameter, $q = Q(y_f)$, while paying the minimum piece-rate to complete the harvest. This solution is similar to a restaurant manager who hires enough servers to handle all the business that comes in, paying them the lowest wage they will accept given how busy it is and the likely amount of tips.\(^1\)

I propose that firms do not observe yields perfectly when deciding a piece-rate. This assumption reflects the unpredictable product losses in many agricultural industries. Pests, plant disease, and weather can often cause significant yield damage that firms do not observe until after a harvest is underway or completed. In the case of SWD infestations, growers can estimate fruit losses due to SWD with trap counts, but a grower’s estimate of fruit losses may be significantly different than her actual fruit losses. Furthermore, I assume that workers know a firm’s true yield parameter. Workers observe yields and determine their earning potential at a location as they pick fruit. Workers also inform each other about potential earnings elsewhere via social networks.

Firms are assumed not to be able to raise or lower the piece-rate during a harvest. Workers may communicate to a firm that yields are lower than expected, but the firm’s reaction is limited because the claims must be validated and each harvest lasts less than a day. Losses can be inconsistent and highly concentrated in some areas, meaning a small sample may not be

\(^1\) Another potential corner solution exists when the minimum piece-rate to harvest any fruit is greater than price of the fruit. This scenario is equivalent to a business shutting down.
sufficient for a yield estimate either. For example, separate 40-fruit samples taken on the same
day from the same raspberry field range from 0-100% infested. Thus I modify equation (3) to
reflect the firm’s inability to predict losses.

\[
\text{(3')} \quad \max_{r_f} \pi_f = (p - c_f) q_f (r_f, \hat{y}_f)
\]

\[
s.t. \quad q_f \leq Q_f (y_f) \quad \text{and} \quad \hat{y}_f = y_f + \varepsilon_f
\]

Rather than knowing the true yield, \( y_f \), a firm uses an estimate, \( \hat{y}_f \), when setting its piece-rate. In the presence of SWD infestations, the yield estimate is informed by fly trappings. This estimate is not perfectly accurate and has an error term, \( \varepsilon \). Note that the partial derivative, \( \frac{\partial \pi}{\partial y} \), is
less than or equal to zero. This result implies that firms who overestimate yields may offer net
earnings below a worker’s reservation wage. Raspberry growers who significantly misjudge worker net earnings when setting a piece-rate won’t be able to hire the profit-maximizing amount
of labor.

This single-period model is repeated each harvest. Raspberry growers hire labor every
few days to pick available fruit for a span of three months. To the extent yields vary predictably
over the course of the season, with fewer berries available at the beginning and end, managers
adjust piece-rates to offer competitive net earnings. However, they cannot perfectly observe all
of the yield variation. When unpredictable losses are sufficiently large, pickers seek greater
earnings elsewhere. Thus fields with significant fruit damage due to SWD may not draw enough
workers to fully harvest the field, despite growers offering piece-rates that appear to be higher
than the market wage.

Firms adjust to unpredictable product losses over time by increasing their piece-rate to
mitigate the risk of under-harvesting when unpredictable losses occur. As the first-order-
condition in equation (4) implies, firms increase their piece-rate until the gain in revenue is equal
to the additional wages. Thus firms will increase their piece-rate until the additional wages are equivalent to the expected product losses from underestimating a piece-rate. Firms may also invest in technology to better predict and control losses, change compensation methods, or exit the industry.

These theoretical results indicate that unpredictable product losses cause some growers to set piece rates too low. This potential market friction may explain some reports of labor shortages. However, the possibility of the result does not demonstrate that the magnitude is plausible. I use the recently introduced invasive species, SWD, as a case study to illustrate the potential magnitude of these unpredictable losses in agricultural production. SWD infestations can drastically reduce the productivity of a field with little warning to growers. Using data collected as part of a scientific study, I estimate the market-distorting effects of the direct fruit losses and harvesting productivity decreases introduced by SWD. An essential component of this analysis includes establishing that yields are significantly reduced and less predictable because of SWD.

**Economics of an Invasive Vinegar Fly**

*Drosophila suzukii*, also known as spotted wing drosophila (SWD), is a vinegar fly originating from East Asia and invasive to California. First detected in California in 2008 and subsequently identified in 2009, SWD is an economic threat to berry and stone fruit producers due to its preference for soft-skinned, ripe fruit. SWD has caused California’s Central Coast raspberry growers estimated production losses as large as 50% in individual fields (Goodhue et al. 2011).

SWD has several unusual characteristics. Of the estimated 3,000 species of *Drosophila*, SWD is one of only two species that has been found to be harmful to undamaged, commercially viable fruit. Most species of vinegar fly breed in decaying plant and fungal material. Because
SWD females possess a serrated ovipositor that can penetrate the skin of soft berries and stone fruits, SWD can infest ripening fruit (Bolda 2009). Furthermore, it is difficult to observe fruit losses associated with SWD. A casual observer can’t differentiate SWD from other vinegar flies and the only indication of an infestation during the first day is a small oviposition sting that can easily be missed upon inspection (Bolda 2010; Lee 2011). Infested fruit deteriorate quickly after this initial period, while remaining difficult to identify as a SWD infestation. Noticeable scarring can occur as soon as a day after the infestation. Within a week, depending on temperatures, adult SWD will emerge, destroying the fruit. Lastly, SWD is hard to exterminate. It spreads quickly, survives the winter, and can use almost any fallen fruit as a host.

SWD causes raspberry growers direct economic losses in three ways. First, fruit that SWD infest decay more quickly, decreasing a field’s yield. After 12 hours, eggs develop into larvae that consume the raspberry as they develop into adulthood for the next three to five days. Second, if the shipper detects significant SWD infestations in sampled fruit, an entire shipment may be rejected. SWD infestations are not visible when harvesting commercially viable fruit. Third, additional insecticide applications are necessary to manage SWD populations. Conventional growers purchase insecticides and hire sprayers that use specialized equipment to apply the product. A lot may be rejected if the grower exceeds residue limits on pesticide use. Organic chemical options have proven mostly ineffective.

Accompanying these direct costs, SWD can also decrease the productivity of harvesting labor. One practice is to reduce the number of days between harvests. Although this 20-33% increase in the frequency of harvests reduces the ripe fruit available for SWD infestations, it also reduces the productivity of labor. Another practice, used primarily by organic growers, is to remove fallen and damaged fruit that would otherwise be a SWD breeding ground. These field
sanitation efforts are extremely labor-intensive; requiring approximately a quarter of a picker’s harvesting capacity to dispose of damaged fruit. Simply removing the fallen fruit is not sufficient for control either. The fruit must be either bagged or frozen in the disposal process to prevent emerging SWD from returning to the field. These practices are not advertised with a piece-rate, but workers quickly adjust their expected earnings.

Growers that don’t implement these labor-intensive practices to manage SWD may still experience reduced labor productivity because of SWD’s potential to reduce yield. As noted earlier, yield and product density are directly related to harvesting productivity. The harvest rate per raspberry picker can vary from one to five trays per hour (Bolda et al. 2012). Worker skill accounts for a significant portion of this variation. An experienced picker is able to harvest 2.5 times the fruit per hour of a novice (Barney 2010). Even accounting for worker skill, a picker’s harvest rate can still vary by a factor of two during a season depending on yields. Roka and Hyman (2012) use a similar example of citrus harvested on a piece-rate to estimate a functional relationship between worker productivity and available crop yield, finding it significant and logarithmic. Considering a field’s yield may be reduced by half because of SWD infestations, SWD can clearly affect worker productivity strictly through its effect on yield.

SWD sampling methods have been proposed and implemented with varying success. The most common method of sampling for SWD thus far has been to set up attractant-based traps composed of apple-cider-vinegar or a yeast-sugar-water solution. These attractant-based traps are easy to make and use, though growers have complained about inconsistent and inaccurate trappings. A more labor-intensive and accurate sampling method is to inspect ripe fruit directly for maggots and eggs. A major advantage of direct fruit sampling is that virtually all fruit fly infestations in commercially viable raspberries are SWD.
These sampling methods represent the observational abilities of the grower in the theoretical model. If a sampling method is particularly inaccurate, then the grower will have a particularly poor estimate of yield in a field. On the other hand, if a grower can perfectly observe losses then there is no labor allocation problem. A rational, profit-maximizing grower will simply adjust the advertised piece-rate so a worker’s net earnings are equivalent to her reservation wage.

Data
Kelly Hamby\textsuperscript{2} and Dr. Frank Zalom\textsuperscript{3} provide data on SWD for organic and conventional raspberry growing sites in Watsonville. These data include SWD detections via trappings and fruit sampling, as well as the amount of pesticide product applied at each site. These are essential variables for modeling the predictability and magnitude of SWD-related fruit losses. SWD detections estimate losses and pesticide applications are a conventional grower’s primary pest control mechanism. The growing sites were commercially managed, and researchers did not control the choice of pest control methods, including insecticides used, the timing of applications, and decisions regarding field sanitation practices. The pest management data include the insecticide products used and application dates and amounts. The organic and conventional raspberry sites had different management practices reflecting the additional restrictions on organic growing. During the study, the organic sites applied SWD-targeted insecticides more often than the conventional sites.

The sampling data span from October 2010 until the end of 2012. The raspberry canes for this study were planted in December a year prior to sampling (2009, 2010, and 2011). The plantings have an 18-month commercial lifespan. Most commercial raspberry canes produce

\begin{footnotesize}
\begin{itemize}
\item \textsuperscript{2} Doctoral Candidate in Entomology at University of California, Davis
\item \textsuperscript{3} Professor of Entomology at University of California, Davis
\end{itemize}
\end{footnotesize}
fruit twice, once in the fall following planting, and then a second time in the subsequent spring and summer. Both harvest seasons last approximately three months, with crews typically harvesting fruit every three to four days depending on yields and pest pressure. The fall harvest season tends to experience greater SWD pressure because the leftover, overripe fruit from another field’s earlier harvest acts as a breeding ground for SWD.

The study placed traps at one organic and conventional site each year. Trapping began at the first fruiting, and continued through the second fruiting. Three types of traps were utilized including an apple-cider-vinegar trap, a yeast-sugar-water trap, and a water control. These traps were checked approximately weekly for the length of the study. At each check, the number of male and female SWD in the trap were identified, counted, and recorded. Starting in September 2011 and continuing for the remainder of the study, non-SWD trapped flies were also recorded.

In 2011 and 2012, SWD infestations were measured weekly by collecting a 40-fruit sample from each site and counting the *Drosophila* larvae present. Since the infestations are not visible, the sampled raspberries were crushed in a sugar-water solution, causing SWD larvae to float and be countable. This randomized sampling was performed when ripe fruit was available for picking. Only ripe fruit, as close to commercial ripeness as possible, were selected for the samples. Figures 1 and 2 report sampled SWD infestations and trappings for conventional and organic sites observed in the study. Some 40-fruit samples contained hundreds of SWD maggots and eggs and the organic fruit samples consistently had more SWD infestations than samples from conventional sites.
A point of reference for a Central Coast raspberry grower’s pest management program is the University of California Cooperative Extension’s “Sample Costs to Produce Fresh Market Raspberries” (Bolda et al. 2012). This report details a pest management program similar to those observed for conventional growers in the sample. Modern chemical SWD management
programs apply malathion and/or zeta-cypermethrin every three weeks, eliminating nearly all SWD infestations. This observation is confirmed in Figure 2, where nearly all SWD infestations were eliminated from sampled conventionally grown raspberries in 2012 using a similar management program. The pesticide use data inform how different management practices affect losses from SWD.

**Analysis of Sampling Efficacy**

The purpose of this analysis is to identify the degree to which growers can observe fruit losses caused by SWD infestations. The infestation sampling data are used to estimate the fruit losses introduced by SWD. The trap sampling data are used to estimate a grower’s ability to detect these unpredictable fruit losses. Analyzing the data confirms that fruit losses due to SWD are significant and unpredictable, fulfilling the premise of the theoretical model. While other sources may cause additional fruit losses, the variation in yields due to SWD infestations is sufficient for illustrating the potential magnitude of unpredictable fruit losses when determining piece-rates.

I compare the efficacy of two commonly used attractant-based traps, an apple-cider-vinegar solution and a yeast-sugar-water solution, using weekly data. Entomologists hypothesize that yeast-based traps may be the solution to the problem of detecting SWD, as different *Drosophila* species have been known to prefer specific yeast varieties (Hamby et al. 2012). Figures 3 and 4 plot the weekly sums of detections and infestations for each trap type. Traps were checked weekly for the entire duration of the study. Note that there are no infestations when fruit is unavailable. The final observed peak in fly trappings is observed after raspberry harvesting has completed; harvest may end while fruit are still available.
Figure 3: Apple-cider-vinegar Trappings

Figure 4: Yeast-sugar-water Trappings
Figure 3 and 4 display readily apparent trends regarding detections and infestations. It is clear that the yeast-sugar-water traps are more effective. They track infestations with moderate accuracy throughout the sample. The apple-cider-vinegar trappings are less accurate than the yeast-sugar-water trappings, lagging infestations by approximately two weeks.

Before comparing the traps’ ability to predict yield losses, I estimate direct fruit losses using the fruit sampling data. Several assumptions are required to estimate these fruit losses. I assume that SWD infestations in a raspberry row are described by a Poisson distribution, with an average equal to the average number of infestations in a fruit sample that period. Since SWD infestations are hard to detect, I assume that small infestations of one to three eggs are harvested in addition to infestation-free fruit. Fruit that is not fully ripe will typically not be infested regardless of the size of the infestation. Thus I assume the portion of under-ripe fruit immune to SWD infestation is given by $1/n$, where $n$ is the number of days since the last harvest. Harvests usually occur every three to four days, but can be as frequent as every other day during peak harvest or as infrequent as once every six days at the start and end of the season.

I also adjust for seasonal differences in raspberry production. Harvest in the second year of production is approximately 10% larger than the first harvest and occurs earlier in the year from May until July. Yields are lower at the beginning and end of each harvest with experts observing that five times as many raspberries can be picked during peak harvest compared to the start or end of the season (Bolda et al. 2012). I assume that yields are distributed throughout a season according to a standard normal distribution, such that peak harvest corresponds to the peak of the distribution. Under these assumptions, Table 1 summarizes the estimated direct fruit losses for conventional and organic growers observed in the study. Recall that the fall harvest is
the first of two harvests in a raspberry field. These loss estimates are derived strictly from the fruit sampling data and do not include labor market effects.

<table>
<thead>
<tr>
<th></th>
<th>Conventional</th>
<th></th>
<th>Organic</th>
<th></th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Summer</td>
<td>Fall</td>
<td>Total</td>
<td>Summer</td>
</tr>
<tr>
<td>Year 1</td>
<td>3.93%</td>
<td>16.1%</td>
<td>9.68%</td>
<td>7.21%</td>
</tr>
<tr>
<td>Year 2</td>
<td>0.0229%</td>
<td>0.124%</td>
<td>0.0710%</td>
<td>14.4%</td>
</tr>
<tr>
<td>Average</td>
<td>1.98%</td>
<td>8.09%</td>
<td>4.87%</td>
<td>10.8%</td>
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</tbody>
</table>

The organic raspberry samples experienced greater SWD-related fruit losses than the conventional ones. The only exception was fall of 2011, when the conventional sites lost an estimated 16% of production in direct fruit losses, excluding labor market effects. In 2012, conventional growers experienced minimal losses due to more frequent and consistent spraying. On average, infestations were more frequent in the fall.

These direct fruit loss estimates are consistent with expert observations. In general, conventional raspberry growers have reduced direct yield losses from SWD to less than 3% of production, similar to the conventional sites sampled in 2012. These control improvements were achieved primarily with additional and better-timed insecticide applications, much like in the sample. However, SWD continues to cause significant losses for organic growers. Organic growers can reduce SWD infestations only with costly, labor-intensive field sanitation practices due to limited chemical control options, and still experience direct fruit losses ranging from 5% to 15% of production, according to field observations. These field observations similarly exclude losses due to labor market effects, which are considered to be significant. The model’s estimates mirror these observations, with organic sites experiencing direct fruit losses between 7% and 16% of production due to SWD infestations.

Using these yield loss estimates, an OLS regression of weekly SWD-related fruit losses on fly trappings is performed for both traps. Table 2 provides estimates of the traps’ accuracy
from the regression analysis. These fly trappings are not separated by sex or species because growers would not be able to observe these characteristics. However, when specifications including the trappings’ sex and type are tested, the model gains explanatory power and appropriately attributes damages to female SWD, the damage-causing agent.

Table 2: Trapping Regression Results

<table>
<thead>
<tr>
<th>Obs. = 676</th>
<th>% Yield Loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trappings</td>
<td>coef.</td>
</tr>
<tr>
<td>Yeast-sugar-water</td>
<td>0.00258***</td>
</tr>
<tr>
<td>Apple-cider-vinegar</td>
<td>0.00197***</td>
</tr>
</tbody>
</table>

*** p < 0.01, ** p < 0.05, * p < 0.10

Yeast-sugar-water traps outperform apple-cider-vinegar traps, but neither demonstrates substantial explanatory power. With a $R^2$ of 0.139, yeast-sugar-water traps fail to explain a majority of the variation in yield. As seen in Figure 5, there isn’t a strong relationship between trappings and infestations.

Figure 5: Average Sampled Infestations and Yeast-sugar-water Trappings

These sampling results support a key assumption in the theoretical model. The grower’s mechanism for observing fruit losses, in this case trapping, fails to explain a majority of the
variation in damage. By implication, fruit losses due to SWD are unpredictable. Considering the potential damage from SWD, it is likely that growers using trapping results will incorrectly judge a field’s yield, and thus offer net earnings below their competitors. Workers who can earn more elsewhere, net of transportation costs, will do so.

**Yield Loss Estimates**

SWD causes significant and unpredictable fruit losses, as demonstrated by the sampling analysis. I proceed to estimate the effects of these losses on piece-rates and production using data collected in the study. I use the direct fruit loss estimates from the yeast-sugar-water trap sampling as a hypothetical grower’s estimate of fruit losses. Comparing these estimated fruit losses to the actual fruit losses from the 40-fruit samples, I determine the degree to which growers may misjudge a worker’s effective earnings, and the resulting production implications. These results support the hypothesis that perceived labor shortages are a result of unpredictable fruit losses interacting with labor markets.

In the simplest version of the theoretical model, the supply of labor is perfectly elastic and a market-clearing effective wage exists, $\bar{w} = r_f \bar{y}$. If a grower does not offer a higher piece-rate to compensate for lower yields, then $w_f \leq \bar{w}$ and the field is not harvested. Typically, growers will balance the risk of total crop loss against the cost of increasing their piece-rate when confronted with this discontinuous production function. I begin by assuming growers interpret their estimate of yield loss derived from yeast-sugar-water trap sampling as the actual yield loss without accounting for the potential error in their estimate. This scenario corresponds to a raspberry grower who believes trappings are perfectly accurate. Thus any overestimate of available yield causes a grower to underestimate the necessary piece-rate, causing a 100% loss.
Using these assumptions, Table 3 reports yield losses for the conventional and organic raspberry growers observed in the study.

<table>
<thead>
<tr>
<th></th>
<th>Conventional</th>
<th></th>
<th>Organic</th>
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<tbody>
<tr>
<td></td>
<td>Summer</td>
<td>Fall</td>
<td>Total</td>
<td>Summer</td>
</tr>
<tr>
<td>Year 1</td>
<td>37.4%</td>
<td>48.3%</td>
<td>42.6%</td>
<td>34.5%</td>
</tr>
<tr>
<td>Year 2</td>
<td>20.2%</td>
<td>6.94%</td>
<td>13.9%</td>
<td>30.3%</td>
</tr>
<tr>
<td>Average</td>
<td>28.8%</td>
<td>27.6%</td>
<td>28.2%</td>
<td>32.4%</td>
</tr>
</tbody>
</table>

These estimates represent a two-dimensional upper bound for the yield losses associated with SWD. First, growers are assumed not to account for the inaccuracy of their fruit loss predictions. Second, the estimates assume a labor elasticity that maximizes total yield losses. If the supply of labor is perfectly elastic, then losses can be as large as 28% and 36% of conventional and organic production. If the supply of labor is perfectly inelastic, the other extreme, total yield losses reduce to the direct fruit losses estimated in Table 1, 5% and 12% of production for the conventional and organic growers in the study.

I continue by relaxing the assumption that the supply of labor is perfectly elastic. Thus I propose a unit elastic supply curve. I assume growers are risk-neutral and profit-maximizing, the reservation piece-rate wage required to complete a harvest during peak yields is $3.00/tray, and that the direct yield loss in each field is equal in proportion to the harvesting productivity reduction. The last assumption is perhaps the most tenuous. Rather than requiring the same number of harvesting labor-hours regardless of yield, it may be that fields with lower yields are harvested with fewer total labor hours because there are fewer fruit available for picking and the reduction in total yield dominates the productivity decrease. The opposite may be true as well;

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4 The average piece-rate to harvest raspberries is $4.00/tray (Bolda et al. 2012). Given the significant variation in worker productivity as yields vary throughout a season, a reservation wage of $3.00/tray during peak harvest is approximately consistent with the piece-rate of $4.00/tray in a harvest with an average yield.
the process of avoiding bad fruit causes productivity losses proportionally larger than the direct fruit losses. Not knowing the exact relationship between a field’s losses and harvesting labor productivity, I default to a simple linear approximation. Under these new assumptions, Table 4 reports yield losses for conventional and organic growers observed in the study.

Table 4: Estimated Yield Losses with a Unit Elastic Supply of Labor and Growers Not Accounting for the Error in Direct Fruit Loss Estimates

<table>
<thead>
<tr>
<th></th>
<th>Summer</th>
<th>Fall</th>
<th>Total</th>
<th>Summer</th>
<th>Fall</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year 1</td>
<td>9.08%</td>
<td>19.0%</td>
<td>13.8%</td>
<td>9.11%</td>
<td>33.3%</td>
<td>20.6%</td>
</tr>
<tr>
<td>Year 2</td>
<td>0.0229%</td>
<td>0.125%</td>
<td>0.0715%</td>
<td>33.1%</td>
<td>19.3%</td>
<td>26.5%</td>
</tr>
<tr>
<td>Average</td>
<td>4.55%</td>
<td>9.58%</td>
<td>6.93%</td>
<td>21.1%</td>
<td>26.3%</td>
<td>23.5%</td>
</tr>
</tbody>
</table>

Average total yield losses for conventional and organic producers are 6.9% and 24%, respectively. These yield loss estimates are larger than the losses determined strictly from fruit sampling, but less than the losses under the assumption of a perfectly competitive labor market. The size of these yield loss estimates indicate that the unpredictable fruit losses introduced by a pest like SWD can significantly increase yield losses relative to an estimate based strictly on direct fruit losses from the pest.

Comparing the magnitude of yield losses between conventional and organic growers, it is clear that the more variable direct fruit losses in organic production increase total yield losses. Under these assumptions, estimated conventional and organic yield losses are 42% and 102% greater, respectively, than when estimated only considering fruit losses. Losses are disproportionately larger for organic growers because they cannot as accurately assess a profit-maximizing piece-rate due to their more variable fruit losses. This result may explain why many organic producers compensate their employees with an hourly wage rather than a piece-rate.

These yield loss estimates have significant implications for the California raspberry industry as a whole. Conventional growers account for approximately 80% of raspberry
production, with the remaining 20% of production being organically produced. Holding acreage constant, total California raspberry production decreased by approximately 10% in the sampled years relative to a counterfactual without SWD’s presence. These production losses were concentrated in the higher value organic crop, with the conventional raspberry crop only experiencing significant infestation pressure in 2011.

However, the model’s estimate of a 10% decrease in raspberry production likely overestimates damages. As stated earlier, organic raspberries are primarily harvested by pickers compensated on an hourly wage, so a majority of organic growers will only experience direct fruit losses and not the additional yield losses from offering too low of a piece-rate. Assuming all organic production is harvested on an hourly wage, the model’s estimate of a 10% decrease in total raspberry production falls to 7.9%. Further, the conventional raspberry losses sampled in 2011 were likely due to the grower not yet having adopted an efficacious control program. Since 2011, conventional raspberry growers have adopted management programs that eliminate nearly all SWD infestations. If the 2011 sampled conventional losses are excluded, then total raspberry production is estimated to decrease by 2.4% because of SWD. These losses are almost entirely composed of organic fruit that is harvested on an hourly wage, so the losses are strictly direct fruit losses.

One direct consequence of yield losses is that raspberry prices should rise if acreage is held constant. Though an own-price elasticity for fresh California raspberries has not been estimated in the economics literature, an own-price elasticity for a comparable commodity, fresh California strawberries, is estimated in Carter et al. (2005). Using that own-price elasticity of demand of -1.9, raspberry prices are expected to increase by 1.3% to 4.2%. Another consequence of these estimated yield losses is that total labor earnings fall, despite growers
increasing their piece-rates. Conventional growers increase piece-rates in response to trappings, with an average increase of 5.6%. Nevertheless, because fields are not fully harvested when growers offer too low of an effective wage given their yield losses, total conventional labor earnings fall by 2.2%.

As a final exercise, I resample the yield loss estimates for conventional growers in 2011 and 2012. These years are resampled separately because of the structural difference in unpredictable fruit losses between the years. Conventional growers in 2011 experienced significant direct fruit losses due to SWD. In 2012 these losses were mitigated by efficacious management methods. The purpose of this resampling is twofold. First, it investigates the robustness of the previous yield loss estimates. Second, resampling enables a more accurate calculation of how growers adjust piece-rates. In the previous results growers did not adjust their piece-rate in response to the risk of yield loss from hiring too few pickers when yield were low. In the resampling analysis, the risk of unpredictable fruit losses from SWD, i.e., the distribution of the observational error in the theoretical model, is known. Therefore, growers adjust wages to account for the risk of yield loss when overvaluing a piece-rate. This wage adjustment is consistent with the first-order condition in equation (4), where a firm equates the marginal revenue increase from a higher wage with the additional costs of offering said wage. By resampling, I simulate the equilibrium wage and yield effects of introducing SWD into conventionally produced Central Coast raspberries.

The simulation results are reported in Table 5. “High Loss” results are resampled from study’s conventional growers in 2011. This is the year the conventional growers in the study under-utilized their effective insecticides and experienced greater losses. “Low Loss” growers
are resampled from 2012, when conventional growers used recommended spraying practices to reduce SWD-related losses to less than 1% of production.

Table 5: Simulated Equilibrium Wage and Yield Effects for Conventional Growers with a Unit Elastic Supply of Labor who Account for the Error in Direct Fruit Loss Estimates

<table>
<thead>
<tr>
<th></th>
<th>Direct Losses</th>
<th></th>
<th>Total Yield</th>
<th></th>
<th>Average Piece-rate</th>
<th></th>
<th>Total Wages</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>coef.</td>
<td>std. dev.</td>
<td>coef.</td>
<td>std. dev.</td>
<td>coef.</td>
<td>std. dev.</td>
<td>coef.</td>
<td>std. dev.</td>
</tr>
<tr>
<td>High Loss</td>
<td>-9.04%</td>
<td>5.13%</td>
<td>-12.0%</td>
<td>8.32%</td>
<td>29.4%</td>
<td>2.68%</td>
<td>21.8%</td>
<td>10.4%</td>
</tr>
<tr>
<td>Low Loss</td>
<td>-0.0691%</td>
<td>0.0949%</td>
<td>-0.0691%</td>
<td>0.0949%</td>
<td>1.01%</td>
<td>0.00283%</td>
<td>1.80%</td>
<td>0.296%</td>
</tr>
</tbody>
</table>

Allowing growers to increase wages in response to the risk of yield loss means that earnings are higher and yield loss is lower than the results corresponding to Table 4. Instead of a 5.6% increase in the average advertised piece-rate, the simulation results imply a 15% increase in the average piece-rate if 2011 and 2012 are weighted equally. Total yield no longer falls by 6.9%, it falls by 6.0%. The effect on total worker earnings is now positive, 12%, as opposed to falling by 2.2%. Growers with high yields offer only slightly higher average piece-rates than they would without SWD, and barely lose any fruit from misjudging workers’ net earnings. Growers with lower, more variable yields offer significantly higher piece-rates to ensure a majority of fruit is harvested when significant, unpredictable fruit losses occur in these fields. Despite an estimated 29% increase in the average piece-rate, these “High Loss” growers still lose 3% of production because of a lack of harvesting labor when fruit losses are significantly larger than predicted. Considering that growers with low yields are advertising above-market piece-rates and still unable to fully harvest their fields, they are likely to report a labor shortage.

These estimates illustrate why growers operating on a piece-rate may report labor shortages. Unpredictable product losses cause growers to occasionally set a piece-rate too low to fully harvest a field, causing high-skilled workers to find work elsewhere. The yield variation can be so large that as much as 70% of a field’s output may not be harvested one week because an underestimated piece-rate, in addition to the fruit losses caused by SWD. Overall, the
estimates provide different perspectives on the potential magnitude of yield loss, from direct fruit losses and from the uncertainty regarding picker productivity when determining a piece-rate.

**Conclusion**

The theoretical model predicts that agricultural producers operating on a piece-rate may perceive labor shortages as they harvest if they are unable to accurately estimate workers’ net earnings. Using SWD as an empirical example, I confirm there are significant product losses, unobservable to managers, affecting a worker’s productivity. Assuming that profit-maximizing workers with access to multiple employment options choose to harvest fields with the highest net earnings, I conclude that growers with lower, more variable yields operating on a piece-rate will be more likely to overestimate their workers’ potential earnings and perceive a labor shortage. For example, simulation results imply conventional growers with significant infestation lose an additional 3.0% of production due to insufficient harvesting labor when they misjudge workers’ earnings. This result explains why growers can advertise piece-rates higher than their competitors and still be unable to hire labor. It may also help explain why organic raspberry growers rely more heavily on hourly wages.

More generally, this analysis investigates a disadvantage of piece-rate compensation. To set a profit-maximizing piece-rate, a firm must be able to estimate a worker’s productivity with some accuracy. If a firm offers too low of a wage, its most productive employees will likely be the first to leave, as they have the most to gain. A firm’s ability to produce when operating on a piece-rate system is directly influenced by its ability to predict workers’ real wages and to offer competitive piece-rates. Some firms may perceive labor shortages, but this market-wide equilibrium is efficient and integrated.
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