Insect population dynamics, pesticide use and farmworker health revisited:

Pesticide choice and risk mitigation

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Abstract

Several policies to reduce worker exposure, dietary and environmental risks are examined in the context of pesticide choice driven by insect population dynamics. Restricted entry policies and taxes have differing impacts for individual and aggregate risks. Limits on application rates have the most consistent impacts on risk.

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Insect population dynamics, pesticide use and farmworker health revisited: Choice and risk mitigation

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In a recent paper, Sunding and Zivin (2000) propose a model of pesticide use and farm worker health risks, comparing the impact of a pesticide tax to that of lengthening the restricted-entry interval prior to harvest, the length of time between a pesticide's application and the time when workers are allowed to enter the field to harvest the crop. At issue is the cost-effectiveness of the policies in reducing health impacts among workers. Lengthening the restricted-entry interval reduces worker exposure by allowing more time for pesticide residues to degrade. However, the model suggests that the longer interval lowers the pest population threshold that triggers a pesticide application. Farmers are induced to apply pesticides to more acres in order to ensure that insects do not damage the crop, thereby exposing more workers to residues. In contrast, the model shows that a tax on pesticides unambiguously reduces the acreage upon which a pesticide is applied, reducing total exposure of the worker population. Sunding and Zivin apply their model to the case of mevinphos, which was used to control aphids on lettuce, in the Salinas Valley of California. In that case, they determine that, despite increases in the acreage treated with mevinphos, a marginal increase in the pre-harvest interval reduces the number of workers poisoned. In fact, the loss of industry profits per poisoning averted is less for an increase in the pre-harvest interval than for a marginal increase in pesticide costs.

This paper modifies the Sunding and Zivin model in a number of ways. We incorporate a second pesticide to examine whether the presence of an alternative alters the outcome of a regulatory policy. Further, we use the model to examine the policy impacts on dietary and environmental risk as well as post-application worker exposure. Three policies, lengthening the restricted-entry interval, a tax and an application rate limit, are shown to have different consequences for risks to the individual and to the worker population. This distinction is critical because the U.S. Environmental Protection Agency (EPA) evaluates occupational risk of pesticide exposure on the basis of the individual. We find that the presence of an alternative pesticide can lead to qualitatively different outcomes. We use as our case study endosulfan, which, like mevinphos, may be used to control aphicids on lettuce. Endosulfan is an organochlorine that has aroused concern not only for farmworker health, but for dietary and environmental risks as well.

The farmers' decision

We follow the Sunding and Zivin (S&Z) model and the Lichtenberg/Zilberman (1986) approach where insect pressure causes damage (in either quantity or quality) resulting in lower profits; insecticides are used to mitigate these damages. Also like S&Z, we make some simplifying assumptions. (1) We assume a discrete damage function that occurs at harvest if pest infestations exceed a marketing standard. This is a reasonable assumption since many fruits and vegetables use such standards to determine marketability. It has the effect of driving the pesticide application decision to the shortest allowable interval before harvest. Thus, we focus on the last application of pesticide during the growing season and assume that other applications are chosen optimally to protect the crop at other times.[1] (2) We assume that the insect growth rate is solely a function of the current population and that there is no infestation from outside. While clearly unrealistic, this greatly simplifies the insect population dynamics. We will, however, relax the assumption that insecticides are completely effective, which means that the insect population is strictly positive at all times. This allows us to measure the trade-off between cost and effectiveness that farmers face as they choose which pesticide to use. Further, we break from the S&Z model in that we recognize that if the farmer is unable to market his or her crop because of a pest infestation, he or she loses the costs of production already invested and that downside risk aversion will lead the farmer to place more weight on this outcome than just the probability of it occurring.

We also correct an error in the way in which S&Z derived the probability of damage from the probability distribution of the pest population at the time of harvest.

We model the farmers' problem as follows. Given a pest population, X_0, at T days before harvest, where T is the restricted interval, the farmer tries to maximize expected profits, defined as

$$E[\pi] = [PY - c - m]\Pr(X_H|\kappa X_0, T \leq X_S) - \beta[c+m]\Pr(X_H|\kappa X_0, T > X_S) \quad \textbf{(1)}$$

where P is the farm gate price, Y is yield, c is the per acre cost of production, m is the cost of pesticide, X_H is the insect population at harvest, $\kappa \in [0,1)$ is the proportion of pests surviving an application of the insecticide, T is the pre-harvest interval (PHI), X_S is the market standard and $\beta \geq 1$ is a risk aversion parameter. In the case of no application, $m = 0$ and $\kappa = 1$.

S&Z determine the critical threshold of insect population, X_0^*, that induces a farmer to apply pesticide. That is, the central question is whether to use an insecticide or not. They note that it is straightforward to extend the model to one of choosing between alternative controls. It is this extension that we pursue. Let X_0^{**} be the threshold at which the expected profit of using one insecticide equals that of the alternative. Then, from (1),

$$\Pr(X_H|\kappa_1 X_0^{**}, T_1 \geq X_s) - \frac{PY + (\beta-1)(c+m_2)}{PY + (\beta-1)(c+m_1)}\Pr(X_H|\kappa_2 X_0^{**}, T_2 \geq X_s) = \frac{m_1 - m_2}{PY + (\beta-1)(c+m_1)} \quad \textbf{(2)}$$

This is almost identical to the result of S&Z (Equation 5′) under risk neutrality ($\beta = 1$) except that P in our model is the farm-gate price, not the price net of production costs. That is, the fact that farmers risk losing their investment if insect infestations result in unmarketable produce will lead them to apply pesticide at a lower threshold of pest pressure than suggested by S&Z. Under risk aversion, where $\beta > 1$, an even higher probability of success is demanded. However, if the insecticide is not

[1]The US EPA distinguishes between the pre-harvest interval (PHI), which is largely aimed at regulating residues left on harvested material to be consumed, and the re-entry interval (REI) that is specifically targeted at workers. PHI considers oral toxicity, residue decay after harvest and the extent to which residues are found in edible portions. REI considers dermal toxicity and the extent to which workers are in contact with treated foliage. For the farmer, the relevant constraint is the longer interval.

completely effective, the risk of losing the cost of the treatment as well as the costs of production, will increase the acceptable probability of failure with no insecticide.

Note that the probability of damage depends on T. A decision has to be made at the longer interval, say that of Alternative 1. The farmer has to consider the possibility that the insect population will explode beyond the capacity of the Alternative 2, especially if $\kappa_2 << \kappa_1$.[2] There is also the possibility that the population will crash and that application is unnecessary. Thus, there may be an option value associated with waiting that increases the expected profits of Alternative 2; but this is outside the scope of our study.

As in S&Z, pest population dynamics are assumed to follow a geometric Brownian motion with intrinsic growth rate, α, and variance parameter, γ, such that $dX = \alpha X\,dt + \gamma X\,\varepsilon$, where X is the insect population and ε is a standard normal variable. The insect population t periods in the future, given an initial population of X_0, is therefore a log-normally distributed variable with expected value, $X_0 e^{\alpha t}$, and variance equal to $X_0^2 e^{2\alpha t}(e^{\gamma^2 t} - 1)$.

If X has a log-normal distribution, then $U = \ln X$, has a normal distribution and $\Pr(X \le x) = \Pr(\ln X \le \ln x) = \Pr(U \le \ln x)$ (Mendenhall, *et al.*, 1990). Further, if U has mean μ and variance σ^2, then X has the expected value $\mathrm{E}[X] = e^{\mu + \sigma^2/2}$ and variance, $\mathrm{V}[X] = e^{2\mu + \sigma^2}(e^{\sigma^2} - 1)$. Setting these expressions equal to the expected value and variance of X_H, we can solve for the parameters of the normally distributed random variable U from which to determine the critical threshold.

$$U \sim N[\ln X_0 + \alpha \mathrm{T} - \gamma^2\,\mathrm{T}/2\,,\ \gamma^2 \mathrm{T}]$$

We can therefore evaluate the $\mathrm{Prob}(X_H | \kappa X_0, \mathrm{T} > X_s) = \mathrm{Prob}(U > \ln X_s)$ by comparing to the standard normal variable z,

$$z = \frac{\ln X_s - (\ln \kappa X_0 + \alpha \mathrm{T} - \gamma^2\,\mathrm{T}/2)}{\sqrt{\gamma^2 \mathrm{T}}} \qquad \textbf{(3)}$$

This is the correct z-score and should replace Equation 8 of S&Z. However, this does not change the qualitative findings of S&Z. Specifically, lengthening the PHI could result in either a decrease or an increase in the threshold for treatment. The direction of change depends, in part, on the relative magnitudes of the intrinsic growth rate, α, and the variability of growth, γ^2, of the insect population. A sufficient condition for $\partial X_0^*/\partial \mathrm{T} < 0$ is that $\alpha > \gamma^2/2$.

How does this relate to pesticide use? Assume that the initial insect population on a field is a random event. Then the probability that $X_0 > X^*$ is identical to the likelihood that insecticide will be applied to that field. Lowering the threshold increases the likelihood that insecticide will be applied. In aggregate, assuming that initial insect populations in a given area are realizations from the same distribution, the $\Pr(X_0 > X^*)$ would be equivalent to the percent of crop area treated. A lower

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[2]An insecticide with a lower κ, or 'kill ratio,' may still be more effective if the restricted interval is sufficiently short.

threshold, given the same insect population distribution, would result in an increase in crop area treated.

Farm worker health risks, dietary risks and environmental risks

Increases in the area treated with insecticide could have important implications for farm worker health and dietary risks, since this would increase the likelihood of exposure to chemical residues. It could also increase environmental impacts, not only by increasing the area treated, but increasing the total amount of a pesticide that enters the environment. For worker re-entry, the EPA evaluates the risks of exposure as a function of the toxicity of the chemical and the likely exposure of a worker, which depends upon the amount of dislodgeable foliar residue found on the crop. One measure of the toxicity of a chemical is the maximum dosage, or level, for which there are no observable adverse effects (NOAEL). Dislodgeable residue is a function of the amount of chemical applied and the length of time since application. Both the amount of chemical that adheres to the plant and its decay rate are generally chemical specific and frequently depend on the crop as well. Worker exposure is also specific to the crop and the particular activity in which the worker is engaged. Harvesting, for example, has a larger coefficient than irrigating because the worker is in more contact with the foliage over a longer period of time.

A proxy for risk to an individual can be formulated as follows.

$$R(t) = \frac{\theta v\, e^{-\delta t}\, q}{\tau} \qquad \textbf{(4)}$$

where $R(t)$ denotes the risk of an adverse reaction at t periods after application, θ measures the amount of chemical residue adhering to the crop, v the amount of the chemical applied in lbs active ingredient (a.i.) per acre, δ is the decay rate, q is the exposure coefficient and τ is the acceptable dose. These parameters would be crop and chemical specific. This measure assumes that risk of an adverse reaction is equivalent to the proportion of expected exposure to the NOAEL. If τ were a threshold below which there was no reaction, a better measure might be $R(t) = \max(0, \theta v e^{-\delta t} q - \tau)$.

Similarly, dietary risk could be measured as a function of the residues left on the harvested material and the oral toxicity. Environmental risk could be measured as a direct function of the amount of pesticide applied, although pesticides with specific risks, such as toxicity to aquatic species, may not be particularly harmful unless transported to other locations.

Note that the risk parameters are not known with certainty. The decay rate, for example, is a function of weather conditions and is subject to considerable variation. Therefore, the regulator chooses the policy or policies (*e.g.*, the restricted interval, T) with the goal that the risk of adverse effects does not exceed a target standard at some level of confidence. For an individual, ideally we would have the probability of an adverse reaction; in aggregate, we want the expected number of adverse reactions out of an exposed population. Thus, an increase in the restricted interval, T, would be expected to reduce human health risks to the individual by allowing more time for the chemical residues to decay. However, as seen above, a longer T may result in a lower insect population threshold at which farmers choose to apply pesticide. A lower threshold could lead to an increase in the area treated, assuming that the pest population in a field has some probability distribution. That increase could lead to a larger number of workers and consumers exposed and raise, in aggregate, the expected number of individuals who have an adverse reaction. Thus, the total impact of a longer re-entry interval depends on the relative magnitudes of these two counteracting effects: an increase in the number of individuals exposed to a lower expected level of residues.

Alternative regulatory policies, including pesticide taxes or limits on the application rate may be more effective in reducing the use of pesticides or the amount used. Sunding and Zivin, and our elaborated model, show that higher pesticide costs unambiguously increase the critical threshold of treatment, which should result in a decrease in area treated. If the application rate remains unchanged on the acres that are still treated, however, then the risk facing an individual has not decreased. A lower application rate on a given area will also reduce health risks to the individual, $\partial R/\partial v > 0$, but the aggregate impact may be muted by changes in area treated. The mere fact that the direction of change is without doubt does not imply that the magnitude of the change will be greater for that policy.

Endosulfan, aphids and lettuce

Endosulfan is an organochlorine or chlorinated hydrocarbon. Developed in the 1950s, it is a fairly broad spectrum insecticide and is frequently used as a foliar application on lettuce. At high levels of exposure it is toxic both by ingestion and by contact with the skin. Endosulfan has also been tied to incidences of fish kills and so poses some environmental risks. The current regulatory restrictions on use of the emulsifiable concentrate formulation of endosulfan include a restricted interval before harvest of 14 days and a maximum application rate of 1 lb a.i./acre. The EPA estimates that worker exposure to endosulfan residues decline below the NOAEL for dermal absorption within 24 hours. Moreover, residues left on lettuce do not, by themselves, exceed accepted levels of dietary risk. However, in light of the fact that endosulfan is currently going through the re-registration process and has been associated with human and environmental risks, the chemical makes a relevant case study. Toxicity and residue data for post-application worker exposure are provided by the EPA Health Effects Division (Sandvig, 2002).[3] All data are shown in Table 1. We use residues remaining at harvest as a proxy for dietary risks, recognizing that below some level no risk actually exists. Our measure of environmental risk is simply the total amount of endosulfan applied in a given area.

Aphids are a common pest to a number of commercial crops. They are small and usually wingless, multiplying asexually for several generations. Periodically, winged generations are produced at which times the aphids reproduce sexually and may migrate for longer distances. They pierce stems and leaves to feed and can leave crops susceptible to disease as well as causing direct damage. Immediately prior to harvest, however, the principal damage is due to reduced marketability rather than lower yields. Most fresh markets place limits on the number of insects found on produce and an entire field's output could be rejected if those limits are exceeded. Aphid population parameters are taken from S&Z and shown in Table 1.

[3]The data for estimating the adherence and decay parameters come from a study of residues on melon leaves.

According to the USDA National Agricultural Statistics Service (2001), lettuce yields in California are about 19 tons/acre and the farm-gate price is about $336/ton. The University of California at Davis' crop budget for head lettuce in Monterey County (Tourte and Smith, 2000), adjusting harvest costs for yields, indicates production costs of around $5830/acre. EPA data provides insecticide costs, which include application costs. A survey of studies in the Arthropod Management Tests (1996, 1998, 1999) provides average effectiveness of endosulfan and imidacloprid, the most commonly used aphicide on lettuce in California. While of less immediate efficacy than endosulfan, the shorter restricted interval of imidacloprid makes it preferable when aphid populations are higher. Insecticide data are shown in Table 1.

Given the data on aphid population dynamics, lettuce production and insecticides, we solve Equation 2 for the critical thresholds between no pesticide application and an application of endosulfan and between the use of endosulfan and of imidacloprid for a range of risk aversion parameter (β) values between 1 (risk neutrality) and 2. Equation 3 is used to evaluate the probabilities of the log-normally distributed variables.

As expected, higher values of β reduce the threshold of application in all scenarios. The upper threshold declines relatively faster so that high risk aversion would eliminate the use of endosulfan in favor of imidacloprid. We settle on a value of $\beta = 1.2$. At that value, the critical threshold for application of endosulfan is 157 aphids/acre. These results are shown in Tables 2 and 3 as the Base Scenario. At an aphid population of 307 aphids/acre, the farmer would switch to imidacloprid.[4] The probability that the aphid population would fall into this range, given mean population of 1265 aphids/acre and standard deviation of 967 aphids/acre, is about 3.5%. This is our expected percentage of lettuce acreage treated with endosulfan, which is consistent with the percent acreage treated for leaf lettuce in all of California, according to the California Environmental Protection Agency (2002). The same data indicate that 8% of head lettuce acreage is treated with endosulfan, which suggests that our model understates actual treatment. Further, California requires a special permit to apply endosulfan due to concerns about risks to fish. Our model estimates desired applications while the permit requirement would limit applications and impose additional costs not considered in our model. However, this model focuses exclusively on the last application before harvest while the California data includes all applications throughout the growing season.

About 60,000 acres of head lettuce are cultivated in Monterey County and another 20,000 acres of romaine (Tourte and Smith, 2000a, 2000b). Thus, the model predicts almost 2800 acres would be treated with endosulfan in the period prior to harvest. The model further predicts that 12.6% of the lettuce acreage would not be treated with insecticide while 83.9% would be treated with imidacloprid. In reality, there are several other aphicides currently available, including dimethoate (7-day PHI) and diazinon (14-day PHI), which may be preferred at different levels of aphid populations.

[4]Since the PHI for imidacloprid is shorter than for endosulfan, the critical threshold actually determines when the farmer would prefer to wait and is based on the expected aphid population T_2 days before harvest. The expected aphid population is given by $X_0 e^{\alpha(T_1 - T_2)}$.

Knowing the critical thresholds permits us to estimate the expected per-acre net revenues (gross receipts less operating and harvest costs) across the range of aphid populations. For untreated acres, they are

$$\int_{-\infty}^{X_0^*} [PY\,\mathrm{Prob}(X_H | X_0 < X_s) - c] \frac{f(x_0)}{F(x_0^*)} dx_0$$

where $f(x_0)$ is the probability distribution of the aphid population and $F(x_0)$ is the cumulative density function. Expected net revenues for acres treated with endosulfan

$$\int_{X_0^*}^{X_0^{**}} [PY\,\mathrm{Prob}(X_H | \kappa_1 X_0 < X_s) - c - m_1] \frac{f(x_0)}{F(x_0^{**}) - F(x_0^*)} dx_0$$

and for acres treated with the alternative

$$\int_{X_0^{**}}^{\infty} [PY\,\mathrm{Prob}(X_H | \kappa_2 X_0 < X_s) - c - m_2] \frac{f(x_0)}{1 - F(x_0^*)} dx_0$$

We make a discrete approximation of expected net revenues by evaluating the probability that the aphid population falls within an interval and using the midpoint of the interval to evaluate the probability of meeting the marketing standard. We calculate expected net revenues on untreated acres to be \$552.52/acre, \$528.26/acre for acres treated with endosulfan, and \$514.59/acre for those treated with the alternative. Given 80,000 total acres and the predicted percentage of the three categories, we calculate that industry cash returns would be \$41.587 million.

Using the residue and toxicity data from Table 1, we calculate endosulfan residues at harvest to be 0.056 $\mu g/cm^2$ of leaf, imlying worker exposure of about 0.13% of the dermal NOAEL (Equation 4).[5] Thus, individual risk is already quite low for workers engaged in hand harvesting. Ideally, the risk measure would give us the probability that an individual would receive a dose of endosulfan exceeding the NOAEL. Then, a measure of risk to the population of workers could be constructed by multiplying this probability by the number of workers engaged in harvesting activities to obtain the expected number of exceedances. S&Z report that it requires 60 persons to harvest an acre of lettuce in one day and we previously noted that 80,000 acres of lettuce are cultivated in Monterey. Simple multiplication gives a population risk measure of 223. This number cannot be interpreted as we would like; however it provides us a means of comparing the impact of alternative policies on workers that combines the individual effect of changes in residues remaining on a treated field with changes in the number of acres treated.

Given the residues/acre at harvest and yields of 19 tons/acre, we calculate residues of 1.5×10^{-6} µg/lb on lettuce harvested from treated acres. Less would probably end up on the edible portions since

[5]In EPA terms, this represents a Marginal Occupational Exposure (MOE) of 750. These values represent the data available at the time this paper was written and could change with new test data. The values used here are to illustrate the methodology and do not represent regulatory standards.

outer leaves are discarded. Again, for an individual, lettuce alone would not result in dietary concerns. Further, given the amount of untreated acres and acres treated with other products, the average level of endosulfan residues in Monterey lettuce would be only 5.1×10^{-8} μg/lb. Residues, of course, do not translate directly into risks and changes in residues do not imply changes in risks as there may be a threshold below which no effects can be detected.

Finally, as a measure of risk to the environment, we calculate a total of 2796 lbs of endosulfan applied in Monterey county. In the next section, we will examine the impact of various policies on residues and amount of chemical applied, which serves as proxies for worker, dietary and environmental risk. We consider how the availability of alternatives can lead to qualitatively as well as quantitatively different impacts.

Policy options and impacts

We examine the impact of three policies on the use of endosulfan and their implications for worker and dietary risks, both at the individual level and the population, and for environmental risk using total lbs a.i. applied as a gross indicator. First, we use the model to predict impacts of different regulatory strategies when an alternative exists. Thus both the lower threshold, X_0^* that determines whether an insecticide will be used, and X_0^{**} that determines the point when the alternative insecticide is chosen, are allowed to vary. We then consider the impacts of the same policies when no alternative exists and the sole issue is whether to use the pesticide or not. This is the S&Z model where only the lower threshold, X_0^*, is allowed to vary. The policies we examine are an extension of the restricted interval, a tax and a reduction in the application rate.

Results of the first policy experiment are shown in Table 2. The base scenario was described above. Increasing T by one day lowers the critical threshold at which a grower would apply endosulfan in order to avoid possible damage from 157 to 131 aphids/acre. The longer time period makes it more likely that the aphid population at harvest would exceed the marketing standard for any initial population. The longer T also lowers the threshold at which a grower would switch to imidacloprid for aphid control from 307 to 245 aphids/acre. The overall impact is a narrowing of the range for which endosulfan is the preferred method of control, leading to a reduction in acreage treated with endosulfan by almost 30%. Revenues of the individual grower change only if they fall within one of the ranges where there is a shift in pesticide use or choice. Expected revenue over the entire distribution declines by 0.03% as a result of higher pest control costs. Worker exposure to residues also declines. The longer T allows for more residues to decay resulting in drop of almost 12% in exposure as a proportion of the NOAEL. The decline in individual risk combined with fewer acres treated results in a decrease of 36% in our measure of risk to the entire worker population. The average cost to the Monterey lettuce industry for a unit decline in population risk is $136. We also see similar declines in expected dietary residues, with reductions in residues on treated lettuce and in mean residues/lb of lettuce. The total amount of endosulfan used also declines by the same proportion as acreage, which could reduce chances for environmental damage.

Many economists believe that market-based incentives, such as taxes, are better policy instruments for insuring that individuals face the full, social cost of using pesticides, including health risks. The

EPA has not historically levied taxes, but we model such a tax to explore the impacts. Our example is a 15% tax on the pesticide, leaving a fixed $10/acre cost of application unchanged. The higher cost increases the threshold at which an application is triggered, to 163 aphids/acre, while it lowers the threshold at which the alternative is preferred, to 197 aphids/acre. Endosulfan is nearly squeezed out of use, with treated acreage declining by almost 80%. Total costs to the lettuce producers, however, are less than with a longer T. Perhaps most striking is that there is no change in risks to the individual working on a treated acre.[6] Aggregate risk declines in proportion to the reduction in treated acres, with an average cost to the industry of $23 for a unit decline in the population risk measure. Mean residues on lettuce in the market decreases, but like worker risk, the expected residues on lettuce from a treated acre remains constant. Thus, if individual risks are the target of regulatory policy, a pesticide tax may not be effective. However, total pounds of endosulfan applied shows the biggest decline of the three policies when an alternative is available. Taxes may be the most appropriate method for dealing with population-type risks.

Our final risk mitigation strategy is a mandatory reduction in the application rate. The effectiveness of endosulfan at a lower rate was obtained from a study by Edelson and Peters (1996). The lower efficacy is partially offset by a reduction in costs, but there is a decline in acres treated of 53%. The lower threshold, X_0^*, declines slightly to 152 aphids/acre, while the upper threshold decreases to 226 aphids/acre. Losses in net revenues to the industry are estimated at about $4000 and are the smallest of the three policies. The reduction in the application rate is the most cost effective policy in terms of risks to the population, at about $22 per unit reduction, and also leads to the largest reduction in risks to the individual working on, or consuming lettuce from, a treated acre. There is also a big reduction in the total amount of endosulfan applied. However, it should be noted that a lower application rate may result in more rapid development of resistance among the target pest population, resulting in greater losses to the industry in the future.

Table 3 presents the results of the same experiment in which the upper threshold is held constant. This is tantamount to the situation where no alternative is available to control the target pest and the only choice is whether to apply the insecticide or not. It also reflects the original S&Z model. We maintain the original threshold so that the base scenarios are comparable. As would be expected, the lack of a viable alternative increases costs to the industry for any regulatory policy compared to the same policy where an alternative exists. However, there are qualitative changes as well. With the upper threshold fixed, acres treated with endosulfan actually expands when T is increased or the application rate reduced. In the case of the restricted interval, while individual risk decreases, the expansion of acreage and the number of new workers exposed leads to a 2.2% increase in our measure of population risk. This is not necessarily bad, if individually the expected exposure is below the threshold where adverse effects occur. The same is true of dietary risk where the residues left on treated lettuce decline, but residues on average increase in the marketed supply. Without an effective alternative, the total amount of endosulfan used would increase with a longer T, which could have implications for environmental risks.

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[6]The model does not allow for a reduction in rate of application following an increase in price. While not totally realistic, in many cases set application rates are recommended and little information is available about efficacy at different rates that would permit the farmer to make marginal adjustments.

In this situation, a reduction in the application rate has the largest impact on all measures of risk, achieving reductions in exposure to residues for individual workers and consumers, and for the both populations, as well as in the total amount of pesticide entering the environment. Total costs are somewhat higher than for a tax, but cost per unit reduction in worker population risk is much less. However, concerns about potential insect resistance must be considered in any restriction on the application rate.

Conclusions

This paper presents a modified version of the Sunding and Zivin model of pest population dynamics and pesticide choice to examine the impacts of different risk mitigation strategies. Our analysis focused on the pre-harvest application of endosulfan for control of aphids in lettuce in order to meet marketing standards of pest infestations. Endosulfan, an organochlorine, poses significant ecological risks, particularly to aquatic species, and may, in some crops, pose human health risks for farmworkers and for consumers. We show that the choice of risk mitigation strategy can have different impacts on different types of risk. Extending the restricted interval is effective at reducing human health risks at the individual level, but may increase the number of people exposed to residues leading to greater risks in the aggregate. However, this may not be of particular concern if, individually, exposure is less than the level at which adverse impacts occur. We also note that a pesticide tax, designed to impose the total social cost of pesticide on the user, may reduce population-level risks, including environmental risks, by decreasing the acreage treated. However, if it does not affect the application rate, a tax may have no impact on the individual risk of a worker entering a treated field or the consumer eating produce from a treated field.

Further, our model shows that qualitatively different impacts may emerge depending on whether alternatives are available for the regulated chemical. In our example, an increase in the restricted interval led to declines in total acres treated and this contributed to decreasing population-level risk and to reducing the total amount of pesticide that would enter the environment. However, in the absence of viable alternatives, the number of acres treated increased with a longer interval as the threshold of treatment was lowered. The increase in acres treated reversed the declines in residues viewed as a whole and increased the total amount of endosulfan used. Without an alternative to endosulfan, a pesticide tax had little overall impact on environmental risks or population risks, while individual risks on treated acres remained unchanged. Thus, the optimal regulatory policy for reducing human health and environmental risks depends on the availability of alternative control measures and the type of risk the regulator needs to address.

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Table 1. Data and parameters for endosulfan applied to lettuce.

Parameter	Description	Value	
Toxicity and Residue Parameters			
θ	deposited residues per lb a.i. ($\mu g/cm^2$)	0.3147	
δ	decay rate ($\mu g/cm^2/day$)	0.1234	
TC	transfer coefficient ($cm^2/hour$)	2500	
BW	body weight (kg)	70	
ET	exposure time (hours/day)	8	
q = TC*ET/BW	exposure coefficient ($cm^2/kg/day$)	285.7	
τ	acceptable dose ($\mu g/kg/day$)	12000	
Aphid Population Parameters			
α	intrinsic growth rate	0.1199	
γ^2	variance of growth rate	0.1152	
X_s	marketing standard (aphids/acre)	11867	
	mean aphids/acre	1265.8	
	std. dev. aphids/acre	967.2	
Lettuce Production Data			
P	farm-gate price ($/ton)	336.00	
Y	yield (ton/acre)	19.0	
c	production and harvest costs ($/acre)	5830.00	
	harvest crew size	60	
	harvested lettuce acreage, Monterey	80,000	
Insecticide Parameters		Endosulfan	Imidacloprid
v	application rate (lbs a.i./acre)	1.0	0.047
m	cost/acre, including application costs	24.30	27.32
κ	effectiveness (% kill)	76.1	67.0
T	restricted interval	14	7

Table 2. Results of policy experiment with alternative to regulated insecticide.

Scenario	Base	T + 1	15% Pesticide Tax	Reduced Application Rate
application rate	1.0	1.0	1.0	0.75
cost (m)	24.30	24.30	26.45	20.73
effectiveness (1-κ)	0.761	0.761	0.761	0.585
T	14	15	14	14
X_0^*	157	131	163	152
X_0^{**}	307	245	197	226
% crop treated	3.5	2.5	0.7	1.6
acres treated % change	2796	2022 -27.7	597 -78.6	1314 -53.0
industry revenues ($ million) % change	41.587	41.576 -0.026	41.583 -0.010	41.583 -0.008
individual risk (% tolerance) % change	0.13	0.12 -11.6	0.13 0.0	0.10 -25.0
population risk % change	223	143 -36.1	48 -78.6	79 -64.8
cost/risk reduction ($)		136	23	22
residues/lb lettuce (treated acres) % change	$1.5x10^{-6}$	$1.3x10^{-6}$ -11.6	$1.5x10^{-6}$ 0.0	$1.1x10^{-6}$ -25.0
mean residues/lb lettuce % change	$5.1x10^{-8}$	$3.3x10^{-8}$ -36.1	$1.1x10^{-8}$ -78.6	$1.8x10^{-8}$ -64.8
total lbs endosulfan applied % change	2796	2022 -27.7	597 -78.6	985 -64.8

Table 3. Results of policy experiment without alternative.

Scenario	Base	T + 1	15% Pesticide Tax	Reduced Application Rate
application rate	1.0	1.0	1.0	0.75
insecticide cost (m)	24.30	24.30	26.45	20.73
effectiveness (1-κ)	0.761	0.761	0.761	0.585
T	14	15	14	14
X_0^*	157	131	163	152
X_0^{**}	307	307	307	307
% crop treated	3.5	4.0	3.4	3.6
acres treated % change	2796	3234 15.7	2693 -3.7	2881 3.0
industry revenues ($ million) % change	41.587	41.575 -0.030	41.581 -0.015	41.580 -0.016
individual risk (% tolerance) % change	0.13	0.12 -11.6	0.13 0.0	0.10 -25.0
population risk % change	223	228 2.2	215 -3.7	173 -22.7
cost/risk reduction ($)		- [1]	756	134
residues/lb lettuce (treated acres) % change	$1.5x10^{-6}$	$1.3x10^{-6}$ -11.6	$1.5x10^{-6}$ 0.0	$1.1x10^{-6}$ -25.0
mean residues/lb lettuce % change	$5.1x10^{-8}$	$5.3x10^{-8}$ 2.2	$5.0x10^{-8}$ -3.7	$4.0x10^{-8}$ -22.7
total lbs endosulfan applied % change	2796	3234 15.7	2393 -3.7	2161 -22.7

[1] The industry incurs costs while population risk increases.