Bioeconomic Modeling of an Imported Disease in California Lettuce

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Abstract

We develop a theoretical and empirical model to measure the benefits and costs of policy options for controlling a seedborne, imported fungus, *Verticillium dahliae*, seriously affecting lettuce production in California. In 1995, the disease Verticillium wilt, caused by the fungus *V. dahliae*, unexpectedly appeared in a lettuce crop in Watsonville, Santa Cruz County. Since then, the disease has spread rapidly through the Parajo Valley, the prime lettuce production region of California. Plant pathologists have determined spinach seeds to be the primary pathway by which the fungus is introduced to the soil (Atallah et al., 2010). Once introduced, the pathogen persists in the soil for many years, affecting subsequent crops. We develop a simulation model to describe growers' profit maximizing decisions regarding which crops to plant, the timing of the plantings, and efforts to control the disease. We also estimate a structural econometric model explaining crop choice decisions made by growers in Monterey County. A simulation model allows for the incorporation of biological parameters estimated from the work of plant pathologists. In addition, we can compare different scenarios, in particular those that growers are hesitant to implement in their fields without knowing the impacts.

Keywords: bioeconomic modeling, Verticillium wilt, lettuce

1 Introduction

Invasive plant pathogens, including fungi, cause an estimated $21 billion in crop losses each year in the United States (Rossman, 2009). California, as a major global trader and agricultural producer, sustains significant economic damage from such pathogens. Fungi damage a wide variety of crops, resulting in yield and quality related losses, reduced exportability, and increased fungicide expenditures (Palm, 2001).

This paper focuses on the fungus *Verticillium dahliae*, which causes a disease known as Verticillium wilt in more than 200 different crops. Verticillium wilt can cause total crop loss in lettuce and other crops such as strawberries and artichokes which are grown in rotation with lettuce. We develop a bioeconomic model to analyze the impacts of this disease on lettuce and, eventually, to estimate the costs of the disease to growers as well as perform a benefit and cost analysis of different policy options to control the pathogen. We estimate a structural econometric model explaining crop and fumigation choices made by growers in Monterey County. No treatment for the disease is available once a crop is affected, so we are able to analyze the impact of the disease by considering only crop and fumigation choices.

Agricultural economics is an important tool for invasive species and pest management research because human behavior and economic activities affect invasions and pests. An extensive literature exists, but there are notable gaps. The history of pest management in economics (Hueth and Regev, 1974; Carlson and Main, 1976; Wu, 2001; Noailly, 2008; McKee et al., 2009) has understandably focused on pests for which treatment is available once crops are affected. Existing work on fungi (Johansson et al., 2006; Gomez, Nunez, and Onal, 2009) focuses on spatial issues regarding the spread of the fungus. This is less relevant in our case as *V. dahliae* spreads mostly through new introductions via spinach seeds rather than from field to field.

A further gap in the literature is the relative lack of papers modeling field level decisions. A number of papers (Lubowski, Plantinga, and Stavins, 2006; Letort and Carpentier,

2009) model crop rotations and crop decisions as shares, i.e., a farmer rotating between two crops would plant half his field to each crop and switch the following year. Only a few papers (Livingston, Roberts, and Rust, 2008; De Pinto and Nelson, 2009) consider plot level decision making. This distinction is relevant because the disease inoculum builds up in the soil and the sequencing of fallowed land and specific crops is meaningful to the propagation and survival of the fungus.

In the remainder of this paper we develop a theoretical and empirical model to measure the benefits and costs of policy options for controlling Verticillium wilt, a disease seriously affecting lettuce production in California. First, we provide background information on the lettuce market, the impacts of Verticillium wilt on lettuce, and the control options analyzed. Next, we conceptualize the bioeconomic framework for the model, which consists of biological relationships, and the profit maximization problem of the grower. We then discuss the available data. The final section concludes with a number of possible extensions to this work.

2 Background

The California lettuce crop, much of which is grown in Monterey County, provides the majority of the lettuce consumed in the United States. This section briefly describes the lettuce industry in Monterey County, as well as the other relevant crops grown in rotation, the history of Verticillium wilt of lettuce, and the available control options.

2.1 Market Information

The California lettuce crop was worth $1.5 billion in 2011. In Monterey County, leaf lettuce and head lettuce are among the top ten crops. Lettuce comprises 50% of produce exports for the county. Approximately ten to fifteen thousand acres are planted to lettuce in Monterey County in each season (spring, summer, and fall). Spinach, broccoli, and strawberries are also important crops to the region.

Spinach seeds, the vector of disease introduction (du Toit, Derie, and Hernandez-Perez, 2005), are not grown in California. The majority of spinach seeds (approximately 70%) are imported from Denmark, the Netherlands, and a small number of other locations with suitable climates. The remaining seeds are supplied by Washington State. Seeds from each of these regions are likely to carry *V. dahliae*.

2.2 Verticillium wilt Information

V. dahliae is a soil borne fungus which affects more than 200 different crops. No effective treatment exists once plants are infected by the fungus (Xiao and Subbarao, 1998; Fradin and Thomma, 2006). The fungus can survive in the soil for ten to fifteen years as microsclerotia, resting structures that are produced as the pathogen colonizes a plant. This allows the fungus to remain in the soil even without a host plant. When a susceptible host is planted, microsclerotia attack through the root structure. If the density of microsclerotia in the soil passes a threshold, a disease known as Verticillium wilt occurs. Lettuce has a much higher threshold than most other crops. The disease appears just before harvest, so inputs have already been applied.

Verticillium wilt first killed a lettuce (*Lactuca sativa* L.) crop in California's Parajo Valley in 1995. Prior to this, lettuce was believed to be immune. Since then, the disease has spread rapidly through the region. By 2010, more than 175 fields, comprising 3,952 acres, were affected by the disease. Nearly half of these fields were newly infected in 2009 or 2010, indicating that the rate of spread has been accelerating in recent years. Although growers have resisted reporting the extent of the disease since 2010, it is likely that the number of affected acres has increased since then.

As shown in figure 1, three main methods of *V. dahliae* introduction exist: local spread from field to field by workers or equipment, introduction via infested lettuce seeds, and introduction via infested imported spinach seeds. Of these, the imported spinach seed hypothesis has been shown to be the main source of the disease (du Toit, Derie, and Hernandez-Perez, 2005). Genetically, the *V. dahliae* population in California lettuce is similar to that found in the spinach seed producing regions, but differentiated from the population in lettuce seed, which is produced locally (Atallah et al., 2010; Atallah, Maruthachalam, and Subbarao, 2012). Furthermore, the rise of the disease in lettuce is correlated over time with large increases in spinach seed production, in particular production with very high density seeding rates (Atallah et al., 2010).

2.3 Control Options

Several methods can mitigate the impacts of this disease. We evaluate these options according to feasibility and cost effectiveness. Figure 1 shows the control methods considered here.

Due to the wide variety of hosts, including weeds, and the length of time microsclerotia can persist in the soil, crop rotation is of limited use. The main options are rotation to strawberries with fumigation and rotation to broccoli, both of which are already grown in the region and rotated with lettuce. Strawberries are extremely susceptible to Verticillium wilt, but returns are high enough and diseases prevalent enough that fumigation prior to planting is very common. The Montreal Protocol has eliminated methyl bromide use for fumigation of vegetable crops such as lettuce; however, strawberries receive a critical-use exemptions and the residual effects from strawberry fumigation provide protection for one or two seasons of lettuce before microsclerotia densities rise (Atallah, Hayes, and Subbarao, 2011). The long term availability of this solution is limited and uncertain. The phaseout of methyl bromide as an ozone depleting substance was supposed to reach 100% in 2005, but critical-use exemptions allow continued use of methyl bromide for certain crops at least through 2014[1] (California Department of Pesticide Regulation, 2010; United States Environmental

[1]Critical-use exemption requests through 2014 specify that up to one third of the California strawberry

Protection Agency, 2012b).

Broccoli is not susceptible to Verticillium wilt and it also reduces the levels of microsclerotia in the soil (Shetty et al., 2000). Some growers have experimented with this solution, but relatively low returns to broccoli in the region prevent this option from becoming a widespread solution. Planting all infected acreage to broccoli may also flood the market, further driving down broccoli prices.

At present, two races, or types, of *V. dahliae* affect lettuce. Resistant lettuce cultivars have been found for race one and are currently being developed commercially. No such resistance has yet been identified for race two. In similar cases with other crops, such as tomatoes, this resistance has proven to be short lived, as the fungus evolves (creating new races) to overcome the resistant varieties. The behavior of other growers is relevant in this case, as the more prevalent a resistant variety is, the more quickly the pathogen may evolve. Analyzing these externalities will allow us to determine the feasibility of solutions that may be outside the grower's control.

Finally, testing or cleaning seeds is an important option for preventing *V. dahliae* from being introduced into a field. Controlling Verticillium wilt through the source, i.e., spinach seeds infested with *V. dahliae*, will have trade implications. Currently, the United States has no phytosanitary restrictions, but Mexico prohibits the importation of seeds if more than ten percent are infected (IPC, 2003).

[Figure 1 about here.]

crop will be fumigated with methyl bromide. The remainder of the crop is treated with alternatives such as chloropicrin or 1,3-Dichloropropene (1,3-D) (United States Environmental Protection Agency, 2012a).

3 Conceptual Bioeconomic Framework

In this paper, we focus on modeling the individual grower's decision making process. In this preliminary work, we consider fields on which only one grower appears.[2]

The main components of the model are a description of the biological relationship among the fungus, the crops, and the control methods and the profit maximization problem of the grower. Both of these components are dynamic. Microsclerotia persist in the soil over time and we assume growers recognize the impacts their crop choices have on future as well as current profits.

3.1 Biological Model

Through close collaboration with plant pathologists specializing in Verticillium wilt, we develop a model of the key biological relationships. We use data gathered from the field as well as from experimental plots to fit parameters. Among the most important relationships are those relating the inoculum density (ID) of the soil (microsclerotia per gram of soil) to the disease incidence (DI) (percentage of infected plants). These ID-DI curves provide a link between the level of microsclerotia and the loss of crops, from which we can estimate the cost. Wu and Subbarao (2012) estimate an ID-DI curve for lettuce, shown in equation (1):

$$\text{Disease Incidence} = 1 - \frac{1}{1 + \exp(r \cdot \text{Inoculum Density} - a)}. \tag{1}$$

The parameters r and a in equation (1) allow us to estimate the prevalence of disease. We calibrate these disease incidence equations depending on the differing thresholds of loss for various crops. Artichokes and strawberries have a low threshold: artichokes experience a 50% loss with microsclerotia densities of five to nine microsclerotia per gram of soil, strawberries

[2]This comprises 94% of the fields in the Monterey County dataset. Multiple growers offers the opportunity to analyze potential strategic behavior, which we leave for future work.

experience a 50% loss with a microsclerotia density of three microsclerotia per gram of soil. By contrast, the comparable threshold for lettuce is approximately 150 microsclerotia per gram of soil. The other crops in the model do not suffer losses. Broccoli is immune, spinach is not affected until after bolting, and cabbage, cauliflower, and celery may be affected by other types of *Verticillium*, but not by the species that affects lettuce. Data are not available at the field level on the density of microsclerotia. Instead, we use proxy variables that affect the level of microsclerotia, which may increase the level or likelihood of microsclerotia in the soil, e.g., a history of spinach, or decrease the level or likelihood of microsclerotia in the soil, e.g., recent fumigation with methyl bromide. The disease incidence estimates show the effect of microsclerotia on the yields of the different crops, while accounting for fumigation status, which are key parameters in the economic model estimating profit. Equation (2) shows these proxy variables:

$$
\begin{aligned}
\text{microsclerotia proxies} = &\theta_{0i} \cdot (\text{crop+fumigation choice}) + \theta_1 \cdot (\text{recent fumigation}) \\
&+ \theta_2 \cdot (\text{spinach history}) + \theta_3 \cdot (\text{recent broccoli}) \\
&+ \delta_4 \cdot (\text{temp*fumigation}) + \delta_5 \cdot (\text{temp*spinach}) \\
&+ \delta_6 \cdot (\text{temp*broccoli}) + \delta_7 \cdot (\text{rainfall*fumigation}) \\
&+ \delta_8 \cdot (\text{rainfall*spinach}) + \delta_9 \cdot (\text{rainfall*broccoli}).
\end{aligned} \tag{2}
$$

In equation (2), the θ parameters describe the effects of different microsclerotia proxy variables. We include a fixed effect for the different crop and fumigation choices, e.g. since lettuce is colonized by the fungus, we expect that this crop choice will have a positive effect on the density of microsclerotia. As mentioned above, fumigation can reduce the levels of microsclerotia even beyond the initial crop, so we include a variable describing fumigation with methyl bromide within the last twelve months. Recent fumigation and recent broccoli are expected to have negative coefficients. These two parameters will allow us to consider the effectiveness of these two control options. Evaluating control options is one of the main research questions we consider.

Another important component is the introduction of microsclerotia on spinach seeds. Du Toit, Derie, and Hernandez-Perez (2005) found 89% of spinach seed samples were infected, with mean incidence 18.51% of seeds per sample and a range of 0.3% to 84.8%. The precise relationship of infected spinach seeds on Verticillium wilt of lettuce is unknown at this time, but we expect this to have a significant and negative effect on per-period profit. Spinach history, a proxy for the probability that the fungus has been introduced into a particular field, is expected to have a positive coefficient in equation (2), i.e., increasing the level of microsclerotia, which in turn is expected to have a negative effect on profit. This allows us to consider the importance of inoculum introduction compared to the subsequent effect of crop rotations to various susceptible crops on the field. One benefit of this model is that it allows for simulations of counterfactuals. For example, we can look at the impact of phytosanitary restriction of less than ten percent infection, as is currently in effect in Mexico, by reducing or eliminating the spinach history variable.

Broccoli can reduce the level of microsclerotia in the soil. Again, we can test the impact of this control option by simulating increases in the history of broccoli and considering the changes in the grower's profit.

Microsclerotia can persist in the soil for ten to fifteen years, but the level slowly declines over time, unless susceptible crops or weeds are present. As the fungus colonizes a susceptible host plant, more microsclerotia are produced. These are incorporated back into the soil as the plant decomposes. Vallad and Subbarao (2008) show that several million microsclerotia are incorporated into the soil by tilling one infected plant. Weather, type of soil, and other factors can play a role in determining the density of microsclerotia at any given time. We include rainfall, temperature, and interaction terms as proxies for the level of microsclerotia to incorporate these effects. The δ parameters in equation (2) are interaction terms between weather variables, rainfall and temperature, which affect microsclerotia survival, and the variables described above. These are included to partially control for the differences in microsclerotia survival rates that cannot be influenced by the grower.

3.2 Economic Model

We use a structural econometric model for the individual's optimal crop and fumigation decisions. In doing so, we assume that growers in our dataset are optimizing profits at the field level. We adopt this model because it allows us to perform counterfactuals and simulations. This will be useful to simulate the effects of different control options, such as a resistant lettuce variety or rotation to broccoli that are not widely available or used. In this analysis, we assume no interaction between agents, although it is possible that on fields with multiple growers, there may be strategic interaction.[3]

For the model, we develop a single agent dynamic optimization problem following that described in the seminal paper by Rust (1987). The action choices are crop and fumigation combinations. The state variables include: months until harvest, density of microsclerotia, previous crop choice and the number of months that choice has been in place, long run crop history for spinach, weather information, prices, and the acreage of the field. Each farmer maximizes the present discounted value of his entire stream of per-period profits. We estimate parameters in the per-period profit functions for each crop by month.

We separate the per-period payoff functions into two categories, one for the susceptible crops and one for the non-susceptible crops. Let $i \in \{1, ..., I\}$ index the different choices (crop *and* fumigation combination). Let $j \in \{1, ..., J\}$ index the different crops, regardless of fumigation. The per-period profit functions also vary over time, but the subscript t is dropped for clarity. The functions for susceptible and immune/resistant crops, respectively, are:

[3]Also, strategic behavior mights result from some of the control strategies. For example, in resistant varieties, the "stock of resistance" will be used up as more growers adopt the technology.

$$
\begin{aligned}
\pi_i =& \beta_{1i} \cdot (\text{crop+fumigation choice}_i) + \beta_{2j} \cdot (\text{yield}_j \cdot \#\text{ months crop j in place}) \\
&+ \beta_{3j} \cdot (\text{price}_j) + \beta_{4j} \cdot (\text{acreage}_j) + \beta_{5j} \cdot (\text{temp}) + \beta_{6j} \cdot (\text{rainfall}) \\
&+ \beta_{7j} \cdot (\#\text{ months until harvest}) + \alpha_j \cdot f_j(\text{microsclerotia proxies}) + \epsilon_i(d_i),
\end{aligned} \tag{3}
$$

and

$$
\begin{aligned}
\pi_i =& \beta_{1i} \cdot (\text{crop+fumigation choice}_i) + \beta_{2j} \cdot (\text{yield}_j \cdot \#\text{ of months crop j in place}) \\
&+ \beta_{3j} \cdot (\text{price}_j) + \beta_{4j} \cdot (\text{acreage}_j) + \beta_{5j} \cdot (\text{temp}) + \beta_{6j} \cdot (\text{rainfall}) \\
&+ \beta_{7j} \cdot (\#\text{ months until harvest}) + \epsilon_i(d_i).
\end{aligned} \tag{4}
$$

In equations (3) and (4), the β parameters generally vary by crop (j), rather than action choice (i), except the parameter β_{1i} on the action choice. The coefficient on crop and fumigation choice, β_{1i}, is a fixed effect for each choice's impact on profit. The coefficient β_{2j} accounts for the time it takes for crops to reach maturity and reflects the grower having the choice to remove a crop early, at the cost of reduced yield. This also captures differing yields across crops and years.

The price variable is the marketing year average price for each crop. Expected crop prices are not available, so this is used to account for growers' expectations of the relative prices of the different crop choices. This is important for our research question as broccoli is a very low margin crop and the feasibility of planting broccoli to reduce the level of microsclerotia is likely to be dependent on the relative prices of crops.

Farms in Monterey County vary greatly in size, from small plots of less than one acre to farms of hundreds or thousands of acres. The acreage coefficient will capture the potentially different profits of farms of different sizes, all else equal.

The temperature and rainfall variables control for aspects of crop yield (and thus profit) that are outside the grower's influence. Our per-period payoff functions are at the monthly level, but not all crops are harvested in all months. Although Monterey grows crops during a large portion of the year, few crops are harvested in the winter months. The variables describing the number of months until harvest account for this fact.

The difference between equations (3) and (4) is the term $\alpha_j \cdot f_j$(microsclerotia proxies), where $f_j(\cdot)$ is the effect of microsclerotia on disease incidence described above. The coefficient α_j represents the severity of the disease and thus the effect on profit. This allows us to distinguish between a crop that may have a high level of disease incidence, but for which the severity is low, meaning that the crop can still be sold, and a crop that has been severely impacted and cannot be sold.

The decision variable is d_i, which is a discrete set of mutually exclusive crop and fumigation choice pairs. Each choice has an associated error term in the econometric model due to unobservables. The outside option is "no crop", which has a normalized payoff of zero. Other crop choices include leaf lettuce, head lettuce, spinach, broccoli, cauliflower, strawberries, celery, artichoke, cabbage, and other crop. Strawberries may be fumigated with methyl bromide and/or chloropicrin, in addition to a count variable of other pesticides. Other crops may be fumigated as well, although methyl bromide may only be used in the early years of the dataset, before the Montreal Protocol restrictions. As expected, most fumigation (approximately 75%) occurs on strawberries.

3.3 Econometric Estimation Technique

The value function for a farmer, which gives the present discounted value of the farmer's entire stream of per-period profits at the optimum, is given by the following Bellman equation:

$$V(S, \epsilon, \Theta) = \max_{d \in D(\mathbf{s})} (\pi(\mathbf{s}, d, \Theta) + \epsilon(d) + \beta \int V(\mathbf{s}', \epsilon', \Theta) d \Pr(\mathbf{s}', \epsilon' | \mathbf{s}, \epsilon, d, \Theta)). \tag{5}$$

To estimate the unknown parameters $\Theta = [\beta, \theta, \delta]$, we use a nested fixed point maximum likelihood estimation technique developed by Rust (1987, 1988). We discretize the action variable, d_t and the vector of state variables, $\mathbf{s}_t$, to implement the econometric model. The decision rule is: $d_t = \gamma(\mathbf{s}_t, \epsilon_t)$; we assume the observed choices are the result of the optimal decision rule that solves the Bellman equation. The state variables obey a Markov process, with a transition density given by: $\Pr(\mathbf{s}_{t+1}, \epsilon_{t+1} | \mathbf{s}_t, d_t, \epsilon_t, \Theta)$. Equation (5) can be rewritten as:

$$V(S, \epsilon, \Theta) = \max_{d \in D(\mathbf{s})} (\pi(\mathbf{s}, d, \Theta) + \epsilon(d) + \beta V^c(\mathbf{s}, \epsilon, d, \Theta)), \tag{6}$$

where $V^c(\cdot)$ is the continuation value. To solve for the unknown parameters, we assume: conditional independence of the state variables and the error term (unobservables), the error terms are distributed multivariate extreme value, and $V^c(\cdot)$ is a unique fixed point to contraction mapping. Under these assumptions, we form a likelihood function of the unknown parameters and maximize the probability of seeing our data, given Θ. This requires a inner fixed point algorithm to compute $V^c(\cdot)$ as rapidly as possible and an outer optimization algorithm to find the maximizing value of Θ, i.e., a fixed point calculation is nested within a maximum likelihood estimation (MLE). Once the empirical model is fully functional and the parameters for the optional decision rule are estimated, we can interpret the parameters described above and begin to perform counterfactual simulations to answer our research questions about the benefits and costs of different control options for Verticillium wilt.

4 Data

To translate the theoretical model into a working empirical model, we discuss the data available. The Pesticide Use Registration data provide the backbone of this analysis, but a number of other data sources are important as well.

4.1 PUR data

The California Department of Pesticide Regulation collects information on all agricultural pesticide use.[4] Each county agricultural commissioner must report monthly data on pesticide use. California was the first state to require full reporting, beginning in 1990; however, a transition period is expected, and we find that data are more reliable with the first few years omitted. Thus, our dataset is comprised of all fields in Monterey County on which any regulated pesticide was applied in the years 1993 to 2010, inclusive. We use these data to create a dataset of monthly observations for each field, with information on the crop planted, the size of the field, the pesticides applied, the grower, the location of the field by township, range, and section, the history of spinach, the recent history of broccoli, and the recent history of methyl bromide.

The data contain the crop planted in each field for each recorded pesticide application. Lettuce is a major crop in Monterey County and the data support this: approximately 50% of the observations are for either head lettuce or leaf lettuce. The crops explicitly included in our model account for nearly 90% of the observations. We account for the many rarely planted crops by including an "other crop" option, for which we use agricultural indices as prices.

To preserve the privacy of growers, their identities are coded. Unfortunately, this prohibits the use of demographic data or information on whether growers are owners or renters. Anecdotal data suggests that some growers specialize in either vegetable crops or berry crops and may rent out land to achieve desired crop rotations. Our data point to a variety of types of growers. The vast majority of fields (94%) have only one grower. We model decision-making on these fields as a infinite horizon problem where the grower chooses the outside option of "no crop" in months during which nothing is planted. For the remaining fields, we split growers into primary and non-primary growers. We designate as primary growers those who plant a field more than 75% of the time and treat these growers as owners

[4] For more information see: `http://www.cdpr.ca.gov/docs/pur/purmain.htm`.

who have an additional option in their choice sets: "rent to another grower".

The non-primary growers are designated as those who plant a field less than 50% of the time. For these growers, 64% plant a maximum of one year in a row, and an additional 17% plant for a maximum of two years in a row (although they may plant for multiple, nonconsecutive years). We consider these growers to be similar to renters, in that they are likely to be less concerned about the future value of the land and their impact on it than owners would be. The renter's problem is related to the problem an owner faces when deciding whether to rent out land, as the owner will anticipate the renter's actions and the land value is affected by the renter's actions and value function.

One complication to this classification system is a very small subset of fields for which the field identification is either miscoded or reused such that the field is not uniquely identified. For 191 fields out of more than 130,000, there are more than five different growers per field. In some cases, there are overlaps related to our collapsing the dataset into monthly observations, i.e., one grower harvests a crop early in the month and another grower plants a different crop near the end of the month, but other cases are clearly in error, where different growers are recorded fumigating different crops on different size plots during the same time period. For our work on the single grower fields, this is not relevant, but we note this small data inconsistency for future work on renters and owners of the land.

For all growers, we are interested in the length of time for which growers plant. We eliminate growers present in 2010, the final year in the sample, because growers might be continuing to plant in subsequent years. In this curtailed dataset, nearly 60% of growers appear in the dataset for seven (possibly nonconsecutive) years. The other years that have higher than expected frequencies are growers who appear in fourteen years of data (8.66% of growers) and those who appear in the entire sample (5.20%). Since many of these growers appear in the year 1993, we also eliminate growers present in the year 1993. Approximately one quarter of growers appear in seven years of this further restricted data set, with an additional 18% appearing for ten years, and 10% appearing for twelve years. Curtailing the sample in this way (by eliminating growers who appear in either the first or last year of the dataset) drastically reduces the number of observations (from approximately seven million in the full dataset to approximately 600,000). This suggests that it is relatively rare for us to see the entire history of a grower, and fits with anecdotal evidence that growers are generally in the business for the long term, justifying our assumption that growers have an infinite time horizon.

4.2 Additional Data

We use a marketing year average price for each crop to represent growers' expectations about prices for each year. The Monterey County Agricultural Commissioner's Office publishes annual crop reports including prices, yields, and acreages for major crops in the county. Monterey County is a major producer of many of the crops included in our model. For most crops, these prices are highly correlated with California-wide price data published by the National Agricultural Statistics Service.

Most data for the biological model are courtesy of Krishna Subbarao, his colleagues, and their published work. These data are not available at the field level to coordinate with the PUR data, but they allow us to calibrate the biological model described previously.

Yearly yield data are taken from the National Agricultural Statistics Service and the Monterey County Agricultural Commissioner's Office. We interact this variable with the number of months a crop has been in place to capture the variation in yield across years as well as the variation within a year as crops mature.

Monthly rainfall and temperature data are from the National Weather Service "Salinas No 2" (Monterey County) government weather station. These data affect both crop growth and the survival of microsclerotia but are outside the control of growers.

5 Concluding Remarks

The economic impacts of Verticillium wilt of lettuce on growers can be quite substantial. We have developed a theoretical model to predict grower's crop and fumigation choices which accounts for the impact of those choices on the microsclerotia of *V. dahliae*. The focal points of both lettuce production and this disease are in Monterey County. We have analyzed the types of growers in the county based on the information reported to the California Department of Pesticide Regulation. This information is by plot of land. We will continue working with these data to implement the empirical portion of this work. In doing so, we will estimate parameters related to the effects of the various microsclerotia proxies on yield, including the effect of potential disease control options, the severity of the disease on the different susceptible crops and the effect of the disease level and severity on profits. Our analysis benefits immensely from the inclusion of biological parameters that allow us to accurately model the cropping system and the disease environment.

In addition to interpreting these parameters, they may also be used to simulate other disease scenarios. The yield and profit effects of the disease will allow us to compare profits grower would receive if Verticillium wilt were not a problem to profits under different disease conditions. Furthermore, by simulating different types of disease controls, we can perform a benefit and cost analysis to aid growers in making future planting decisions.

In addition to the work in progress on the single grower fields, many possible extensions exist. We plan to extend the model to include fields with multiple growers. Capturing the interaction between growers who act like owners and those who act like renters will provide additional realism to the model. Currently, we assume the growers are profit maximizing, which implies that they are risk neutral. We could also check for risk aversion.

We would also like to incorporate more information about the control options, in particular the development of resistant varieties and cleaning or seed testing methods. Currently, the negative economic impacts of Verticillium wilt on lettuce are primarily felt by growers in the local region, but attempts to limit new introductions may have international trade implications for the seed industry.

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Figure 1: Diagram of Verticillium wilt: Causes and Control Options