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RESEARCH ARTICLE

The economics of managing Verticillium wilt, an imported disease in California lettuce

Successfully controlling Verticillium wilt requires future investment, but there is no incentive for short-term growers who rent land to absorb those costs; nor is there incentive for spinach seed companies to test or clean spinach seeds.

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Abstract

Verticillium dahliae is a soilborne fungus that is introduced to the soil via infested spinach seeds and that causes lettuce to be afflicted with Verticillium wilt. This disease has spread rapidly through the Salinas Valley, the prime lettuce production region of California. Verticillium wilt can be prevented or controlled by the grower by fumigating, planting broccoli, or not planting spinach. Because these control options require long-term investment for future gain, renters might not take the steps needed to control Verticillium wilt. Verticillium wilt can also be prevented or controlled by a spinach seed company through testing and cleaning the spinach seeds. However, seed companies are unwilling to test or clean spinach seeds, as they are not affected by this disease. We discuss our research on the externalities that arise with renters, and between seed companies and growers, due to Verticillium wilt. These externalities have important implications for the management of Verticillium wilt in particular, and for the management of diseases in agriculture in general.

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

The value of California's lettuce crop, which represents the majority of the United States' lettuce production, was $2.0 billion in 2016 (National Agricultural Statistics Service 2017). Measured by value, lettuce ranks in the top 10 agricultural commodities produced in California (National Agricultural Statistics Service 2015). Much of California's lettuce crop is grown in Monterey County, where lettuce production value is 27% of the county's agricultural production value (Monterey County Agricultural Commissioner 2015). Approximately 10,000 to 15,000 acres are planted to

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Lettuce ranks in the top 10 agricultural commodities produced in California and much of it is grown in Monterey County. *Verticillium dahliae*, a soilborne fungus that causes Verticillium wilt, first appeared in lettuce in 1995 in Watsonville. The main source of the disease is infested spinach seeds. Lettuce and spinach are often planted in sequence.

Marita Cantwell

lettuce in Monterey County each season (spring, summer and fall). Spinach, broccoli and strawberries are also important crops in the region.

This paper discusses the economics of managing *Verticillium dahliae*, a soilborne fungus that is introduced to the soil via infested spinach seeds and that causes lettuce to be afflicted with Verticillium wilt, which first appeared in lettuce in 1995 in Watsonville, California. Since then, the disease has spread rapidly through the Salinas Valley, the prime lettuce production region of California.

Verticillium wilt

No effective treatment exists once plants are infected by *V. dahliae* (Fradin and Thommas 2006; Xiao and Subbarao 1998). The fungus can survive in the soil for 14 years as microsclerotia, which are resting structures that are produced as the pathogen colonizes a plant. This system allows the fungus to remain in the soil even without a host plant. When a susceptible host is planted, microsclerotia attack through the root, enter the water conducting tissue, and interfere with the water uptake and transport through the plant. If the density of microsclerotia in the soil passes a threshold, a disease known as Verticillium wilt occurs.

Verticillium wilt first killed a lettuce crop in California's Parajo Valley in 1995. Prior to 1995, lettuce was believed to be immune. By 2010, more than 150 fields were known to be infected with Verticillium wilt (Atallah et al. 2011), amounting to more than 4,000 acres. As not all the fields that were infected by 2010 were known at the time Atallah et al. (2011) was published, the number of fields affected by 2010 is actually even higher, numbering over 175 fields (Subbarao 2011). 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.

V. dahliae is introduced to the soil in three possible ways. First, it can be spread locally from field to field by workers or equipment. Local spread is a relatively minor contributor, however, and growers have taken steps to mitigate this issue themselves, for example by cleaning equipment before moving between fields.

A second way in which Verticillium wilt is introduced to the soil is via infested lettuce seeds. However, studies of commercial lettuce seed lots from around the world show that fewer than 18% tested positive for *V. dahliae* and, of those, the maximum incidence of infection was less than 5% (Atallah et al. 2011). These relatively low levels do not cause Verticillium wilt in lettuce at an epidemic level. Models of the disease suggest that it would be necessary for lettuce seed to have an incidence of infection of at least 5% and be planted for three to five seasons in order for the disease to appear, with at least five subsequent seasons required for the high disease levels currently seen (Atallah et al. 2011).

The third way in which Verticillium wilt is introduced to the soil is via infested spinach seeds. Spinach seeds have been shown to be the main source of the disease (du Toit et al. 2005; Short et al. 2015); 89% of spinach seed samples are infected, with an incidence of infected seeds per sample of mean 18.51% and range 0.3% to 84.8% (du Toit et al. 2005). The precise impact of planting infected spinach seeds on Verticillium wilt of lettuce was recently assessed and proven to be the cause of the disease on lettuce (Short et al. 2015). The pathogen isolated from infected lettuce plants is genetically identical to the pathogen carried on spinach seeds (Atallah et al. 2010).

Infected spinach seeds carry an average of 200 to 300 microsclerotia per seed (Maruthachalam et al. 2013). As spinach crops are seeded at up to 9 million seeds per hectare for baby leaf spinach, even a small proportion of infected seeds can introduce many microsclerotia (du Toit and Hernandez-Perez 2005).

One method for controlling Verticillium wilt has been to fumigate with methyl bromide. As methyl bromide is an ozone-depleting substance, the Montreal Protocol has eliminated its use for fumigation of vegetable crops such as lettuce; however, certain crops such as strawberries received critical-use exemptions (CUEs) through 2016 (California Department of Pesticide Regulation 2010; U.S. Environmental Protection Agency 2017), and the residual effects from strawberry fumigation provide protection for one or two seasons of lettuce before microsclerotia densities rise (Atallah et al. 2011). The long-term availability of this solution is limited and uncertain. The California Strawberry Commission has still been attempting to obtain CUEs for 2017, but so far has not been successful and methyl bromide cannot be used currently. Other fumigants, including chloropicrin and 1,2-dichloropropene, have replaced methyl bromide with mixed results in preventing Verticillium wilt.

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Lettuce infected with verticillium wilt. No effective treatment exists once plants are infected. Verticillium wilt can be controlled with soil fumigation, planting crops other than spinach, and the testing and cleaning spinach seeds.

A second method for controlling Verticillium wilt is to plant broccoli. Broccoli is not susceptible to Verticillium wilt and it also reduces the levels of microsclerotia in the soil (Shetty et al. 2000; Subbarao and Hubbard 1996; Subbarao et al. 1999). Some growers have experimented with this solution, but relatively low returns from 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. With a season length of 2 to 3 months, between 4 and 6 crops of broccoli could be planted within a year, and multiple crops of broccoli would be necessary to reduce Verticillium wilt. Using the very conservative estimate of 4,000 acres infected by Verticillium wilt, this could result in harvested acres of broccoli ranging from 16,000 to 24,000 acres per year (or 32,000 to 48,000 acres if infected acres are equal to 8,000). Given that approximately 50,000 acres of broccoli are harvested in Monterey County annually, planting all infected acreage to broccoli could nearly double county broccoli production. Furthermore, if more acres than expected are infested (on average, about 35,000 acres are planted to lettuce each season, for three seasons per year, and resulting in approximately 100,000 harvested acres per year), the level of broccoli production required to use planting broccoli as a control method would be even greater.

Verticillium wilt can be prevented or controlled by the grower by fumigating, planting broccoli, or not planting spinach.

A third method for controlling Verticillium wilt is to not plant spinach, since spinach seeds are the vector of pathogen introduction (du Toit et al. 2005). Growers who use this control method must forgo any profits they would have received if they planted spinach, relative to the profits from any low-return crop they might plant instead.

In addition to the control measures that the grower can take, Verticillium wilt can also be prevented or controlled by a spinach seed company through testing and cleaning the spinach seeds. Testing or cleaning seeds is an important option for preventing *V. dahliae*. from being introduced into a field, but can be uncertain and potentially costly. Although *V. dahliae* cannot be completely eliminated by seed cleaning, incidence levels in spinach seed can be significantly reduced (du Toit and Hernandez-Perez 2005). Very recent developments in testing procedures suggest that testing spinach seed for *V. dahliae* might soon be feasible on a commercial basis. Moreover, a very recent innovation speeds up testing spinach seeds. Previously, testing for *V. dahliae* in spinach seeds took approximately 2 weeks and could not accurately distinguish between pathogenic and nonpathogenic species (Duressa et al. 2012). This new method takes only one day to complete, is highly sensitive (as it can detect one infected seed out of 100), and can distinguish among species (Duressa et al. 2012).

Verticillium wilt can therefore be prevented or controlled by the grower by fumigating with methyl bromide, planting broccoli, or not planting spinach. Control options such as fumigating with methyl bromide and planting broccoli require long-term investment for future gain. Verticillium wilt can also be prevented or controlled by the spinach seed company by testing and cleaning the spinach seeds. However, as we explain below, all these control options are plagued with externalities.

Externalities

An externality arises whenever the actions of one individual or firm have a direct, unintentional, and uncompensated effect on the well-being of another individual or the profits of another firm (Keohane and Olmstead 2016). When individuals or firms make their decisions, they generally do not account for any externalities they may impose on others. When individuals or firms do not account for those externalities, their decisions may not be optimal from a societal point of view. In this paper, we discuss two externalities that arise due to Verticillium wilt and review our research on these externalities.

Intertemporal externality

When faced with managing a disease that requires future investment, short- and long-term decision-makers may have different incentives and choose to manage the disease differently. Because the options for controlling Verticillium wilt require long-term investments for future gain, an intertemporal externality arises with short-term growers, who are likely to rent the land for only a short period of time. Renters, therefore, might not make the long-term investments needed to control Verticillium wilt. As a consequence, future renters and the landowner may suffer from decisions of previous renters not to invest in control options. Thus, decisions made by current renters impose an intertemporal externality on future renters and the landowner. The intertemporal externality is depicted in figure 1.

Anecdotal evidence suggests that land values can drop as much as 25% when it is discovered that acreage is contaminated with *V. dahliae*. Landowners have also reported renters asking for reduced rent because of *V. dahliae* contamination.

In Carroll et al. (2017b), we analyze the factors that affect crop choice and fumigation decisions made by growers and consider how the decisions of long-term growers (whom we call "owners") differ from those of short-term growers (whom we call "renters"). We examine whether existing renter contracts internalize the intertemporal externality that a renter's decisions today impose on future renters and the landowner, and analyze the implications of renting versus owning land on welfare.

To analyze these issues, we develop and estimate a dynamic structural econometric model of growers' dynamic crop choice and fumigation decisions and compare the decision-making of long-term growers (owners), who have an infinite horizon, with that of short-term growers (renters), who have a finite horizon. A structural econometric model is one that combines economic theory with a statistical model; a model is dynamic if it models decision-making over time. A structural econometric model generates parameter estimates with direct economic interpretations. We use the parameter estimates to simulate counterfactual scenarios regarding renting and owning.

We use a dynamic model for several reasons. First, control options such as methyl bromide fumigation and planting broccoli are investments, in the sense that they require expending money or foregoing profit in the current period in exchange for possible future benefit. Second, these investments take place under uncertainty. The investments are irreversible, there is uncertainty over the reward from investment, and growers have leeway over the timing of investments. Thus, there is an option value to waiting which requires a dynamic model (Dixit and Pindyck 1994). A third reason to use a dynamic model is that long-term growers and short-term growers have different planning horizons, implying that short-term growers may be less willing to make the long-term investments needed to control Verticillium wilt. A dynamic model with different time horizons for long-term and short-term growers best enables us to compare these two types of growers.

When it is costly for the renter to prevent Verticillium wilt, and costly for the landowner to observe the renter's actions, a contract may not suffice to internalize the intertemporal externality. Furthermore, if contracts that include stipulations to control Verticillium wilt are not the norm in the area, highly restrictive contracts may be less desirable and receive lower rents.

Although we do not have data on contracts, it is a testable empirical question whether existing renter contracts internalize the intertemporal externality imposed by renters on future renters and the landowner. We compare the results from short-term growers with those from long-term growers, and also compare results from short-term growers early in the time period (1993 to 2000) with those later in the time period (2001 to 2011). Verticillium wilt was not identified on lettuce until 1995 and the likely sources of the disease were not known until years later. If contracting internalized this externality, we would expect to see more evidence in the later period.

We apply our dynamic structural econometric model to Pesticide Use Reporting (PUR) data from the California Department of Pesticide Regulation. Our data set is composed of all fields in Monterey County on which any regulated pesticide was applied in the years 1993 to 2011, inclusive. Additional data on prices, yields and acreage come from the Monterey Agricultural Commissioner's Office.

According to our results in Carroll et al. (2017b), we find that although methyl bromide fumigation and planting broccoli can both be effective control options, growers with a short time horizon have no incentive to commit to such actions. In contrast, long-term decision-making by owners yields higher average present discounted value of per-period welfare and more use of the control options, likely due to differences in incentives faced by owners versus renters, differences in the degree to which the intertemporal externality is internalized by owners versus renters, the severity of Verticillium wilt, the effectiveness of control options and rental contracts, and a longer planning horizon.

Although contracts can be a potential method for internalizing an externality between different parties, our empirical results show that existing rental contracts do not fully internalize the intertemporal externality imposed by renters on future renters and the landowner. This outcome may be because of the relatively recent development of the disease and knowledge of its causes, more restrictive contracts not being the norm, the possibility of land unknowingly being contaminated before rental, or difficulty in enforcing or monitoring aspects of the contract such as whether boots and equipment are washed between fields.

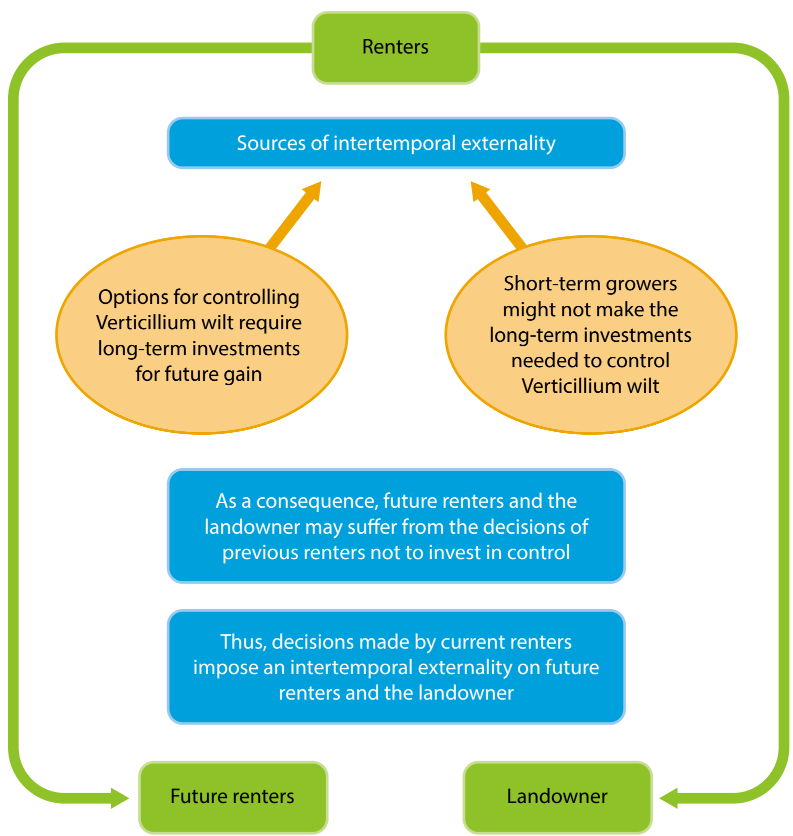

Fig. 1. Intertemporal externality. As indicated by the green arrows, the intertemporal externality is an externality that renters impose on the future renters and the landowner.

Supply chain externality

In addition to the intertemporal externality, a second externality that arises due to Verticillium wilt is a supply chain externality between companies selling spinach seed and growers who may grow lettuce. Growers wish to protect their fields from Verticillium wilt, but they cannot easily prevent introduction of the disease by spinach seeds when spinach is planted without incurring testing costs and cleaning fees. Currently, seed companies are unwilling to test or clean spinach seeds, especially as spinach producers are not affected by this disease. Thus, decisions made by seed companies regarding whether and how much to test or clean spinach seeds impose a supply chain externality on growers. In particular, decisions by seed companies not to test or clean spinach seeds impose a negative supply chain externality on growers.

There are several reasons why the supply chain externality exists between spinach seed companies and growers. First, testing and cleaning spinach seeds is uncertain and potentially costly, and although testing or cleaning seeds may prevent *V. dahliae* from being introduced into a field, spinach seed companies may not have an incentive to test or clean spinach seeds, as they do not internalize the costs that infected spinach seeds impose on growers.

A second reason the supply chain externality exists is that, owing to asymmetric information, the price signal for tested and cleaned spinach seed versus contaminated seed is weak. Growers buying spinach seeds with the intention of planting lettuce in the following season may be willing to pay a very high price for clean seed after accounting for their potential loss in harvest revenue for lettuce and penalties for breaking contracts with lettuce shippers if their lettuce is afflicted with Verticillium wilt. However, if a seed company has infected seed that it cannot otherwise sell, the seed company may be willing to pay a high price to clean the seed without passing on the cost if the seed company wishes to maintain market share (Dale Krowlikowski, Head of Operations and Research, Germains Technology Group, personal communication, 2015). Thus, owing to asymmetric information, there is no direct price signal between seed companies and growers, and, as a consequence, seed companies impose an externality on growers that they do not internalize.

A third reason the supply chain externality exists between spinach seed companies and growers is that Verticillium wilt in lettuce is an example of a market failure in which transaction costs between seed companies and lettuce growers prevent them from reaching a potentially more efficient equilibrium solution. Transaction costs increase with the number of agents. There are a large number of growers attempting to bargain with a relatively small number of seed companies. Due to the small number of seed companies, some growers are hesitant to resort to legal means, such as working toward a seed testing or cleaning requirement from the county agricultural commissioner, lest seed companies decide to leave the market. There are precedents for such requirements; for example, the office of the Monterey County Agricultural Commissioner currently enforces a host-free period to prevent the establishment of lettuce mosaic virus and also enforces a lettuce seed "indexing" or testing requirement to prevent the introduction of the disease.

Thus, owing to the lack of incentives for spinach seed companies to test or clean spinach seeds, asymmetric information, and transaction costs, spinach seed companies are unwilling to test or clean spinach seeds. Thus, decisions made by seed companies not to test or clean spinach seeds impose a negative supply chain externality on growers. The supply chain externality is depicted in figure 2.

In Carroll et al. (2017a), we analyze the supply chain externality between growers and seed companies. We calculate the benefits to growers from testing and cleaning spinach seed by simulating growers' optimal decisions and welfare under different levels of seed testing and cleaning. We then estimate the spinach seed company's cost to test and clean spinach seeds in order to reduce the level of microsclerotia, and compare the spinach seed company's cost to the grower's benefits. Because seed cleaning cost data are not available, we use several functional forms and parameters to estimate potential cost functions. We then use the benefits

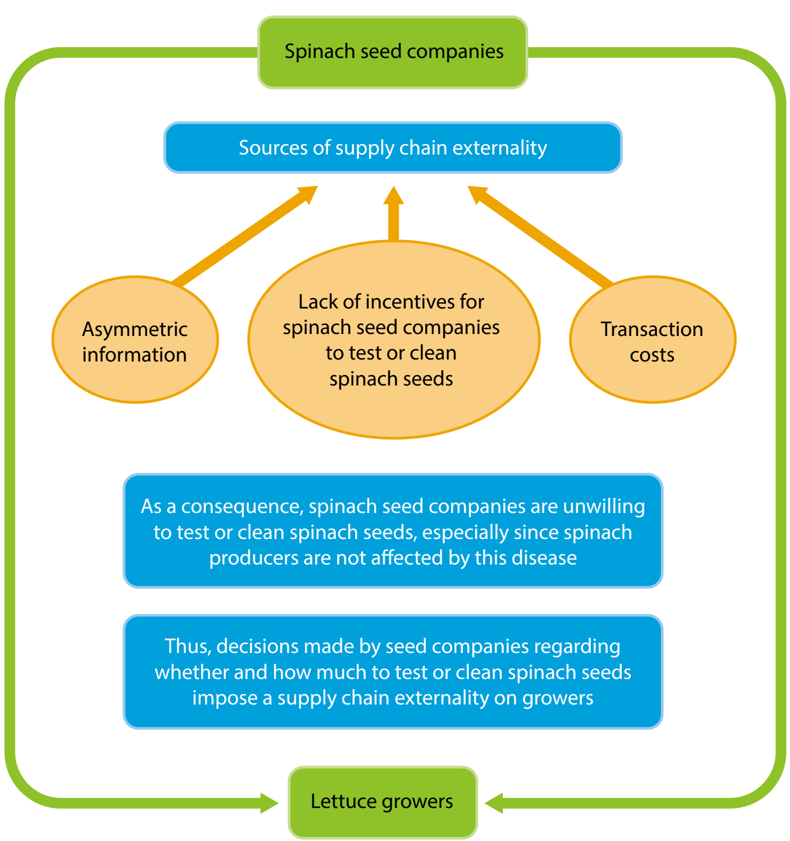

Fig. 2. Supply chain externality. As indicated by the green arrows, the supply chain externality is an externality that spinach seed companies impose on lettuce growers.

and costs to determine the welfare maximizing level of seed testing and cleaning.

According to our results in Carroll et al. (2017a) using data over the entire time period, we find that in more than half of the cases, the socially optimal amount of spinach seed testing and cleaning is more than what arises when the externality is not internalized (the status quo). Significant welfare gains arise only when the seed company tests and cleans the spinach seeds so thoroughly that planting spinach does not have any significant negative effect on grower payoffs after controlling for spinach price. In other cases, even though it maximizes welfare, the socially optimal amount of spinach seed testing and cleaning does not yield any welfare gains.

Thus, we find in Carroll et al. (2017a) that a cooperative solution would increase welfare, and in most cases, a cooperative solution would require that the spinach seed company engage in more spinach seed testing and cleaning than in the status quo. Our work regarding the supply chain externality between seed companies and growers sheds light on how treatment of spinach seeds could potentially reduce externalities between seed companies and growers.

Conclusion

When managing crop disease, it is important to consider any externalities that may plague the available control options. In this paper, we discuss our research on the externalities that arise with short-term growers (Carroll et al. 2017b) and between seed companies and growers (Carroll et al. 2017a) due to Verticillium wilt, which has important implications for the management of Verticillium wilt in particular, and also for the management of diseases in agriculture in general. The results of our research are of interest to policymakers, the agricultural industry, and academics alike. CA

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