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## The control of invasive species on private property with neighbor-to-neighbor spillovers

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### Abstract

Invasive pests cross property boundaries. Property managers may have private incentives to control invasive species despite not having sufficient incentive to fully internalize the external costs of their role in spreading the invasion. Each property manager has a right to future use of his own property, but his property may abut others' properties enabling spread of an invasive species. The incentives for a foresighted property manager to control invasive species have received little attention. We consider the efforts of a foresighted property manager who has rights to future use of a property and has the ability to engage in repeated, discrete control activities. We find that higher rates of dispersal, associated with proximity to neighboring properties, reduce the private incentives for control. Controlling species at one location provides incentives to control at a neighboring location. Control at neighboring locations are strategic complements and coupled with spatial heterogeneity lead to a weaker-link public good problem, in which each property owner is unable to fully appropriate the benefits of his own control activity. Future-use rights and private costs suggest that there is scope for a series of Coase-like exchanges to internalize much of the costs associated with species invasion. Pigouvian taxes on invasive species potentially have qualitatively perverse behavioral effects. A tax with a strong income effect (e.g, failure of effective revenue recycling) can reduce the value of property assets and diminish the incentive to manage insects on one's own property.

### Keywords

Asian citrus psyllid; bioeconomics; citrus; dynamic programming; invasive species; property rights; repeat optimal stopping; spatial externalities; value function approximation

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## 1. Introduction

Spatial interactions between economic agents are often mediated through property, and markets often fail to internalize environmental processes that cross property boundaries creating spatial externalities (Smith et al. 2009a). The fact that flows generating spatial externalities cross boundaries implies that spatial externalities are transferable and depletable, in the sense that failing to control externality transfers damage to another location (Bird 1987). Bird (1987) argues that transferable externalities can be passed along in space or time. The incentive to engage in abatement and filter the externality (Shogren and Crocker 1991) may be strong if the externality cannot be fully transferred in space and can only be transferred a short distance into the future, retaining the damaging stock on one's own property. Such a scenario makes some level of abatement in the land manager's self-interest. Alternatively, when an externality is transferred in space, the property rights of the receiver of the externality are attenuated, in that his property right in space does not give exclusive control over ecological processes. Costello and Kaffine (2008) suggest that even attenuated property rights may help reduce rent dissipation in the commons.<sup>1</sup> A related question is how do spatial ecological interactions attenuate the value and incentives associated with traditionally defined real property, and what does this mean for the transfer or filtering of spatial-dynamic externalities?

Invasive species are an archetypal spatial environmental problem causing \$100s of billions in damages (Born et al. 2005; Pimentel et al. 2000; Xu et al. 2006). Failing to control invasive species can be framed as under provision of a public good, but is more often framed as a "biological pollution" problem (Horan et al. 2002). Pricing the externality at the social cost is expected to eliminate the externality, and Pigouvian taxes and Coasian systems of exchange are common mechanisms for correcting externalities. A complete property right would enable a manager to exclude undesirable species introductions.<sup>2</sup> But, unless individual properties are very large, property rights likely provide insufficient incentives to manage spatial-dynamic processes at the socially optimal level (Hansen and Libecap 2004) and ecological processes are likely to extend across property boundaries. Furthermore, jointness of supply, e.g., if invasive species are established on multiple properties, can limit the feasibility and appropriateness of a tax (Hansen 2002).

We model the efforts of a foresighted property manager, who has rights to future use of a property and the ability to spray pesticide on a per acre bases, a realistic but blunt management instrument, to control the growth of an invasive pest population on his property, as a repeated optimal stopping problem (similar to Saphores 2000).<sup>3</sup> We extend the model to investigate how property based control incentives influence the interactions between neighbors. Delaying spraying simultaneously transfers the pest externality in both

<sup>1</sup>Attenuated spatial property rights may also have a finite time horizon.

<sup>2</sup>We refer to spatial property rights and not ownership because it is possible that more limited rights provide incentive for control. For example, a rancher with a grazing right to public land, and the ability to exclude other ranchers, is more likely to control an invasive weed than if the area were grazed as a commons. This is true even though the rancher does not own the range.

<sup>3</sup>Blunt management instruments cannot be used in a continuous way according to equimarginal principle, and many realistic land management instruments fall into this category. When pesticide is sprayed on a per area based the treatment level is not influence by the size of the pest population. Another example is engaging biosecurity measures such as fencing to protect livestock from wildlife carrying disease (Horan et al. 2008).

space - to neighbors, and in time - to one's self in the future. The decision to delay spraying, and transfer the externality, or spray, and abate the externality, depends on whether the bulk of the externality is transferred to neighbors. Furthermore, the neighbor's response (Geaun 1993; Shaw and Shaw 1991), or one's future plans influence the decision. We use our model to investigate market based policies – policies that alter management incentives – that could improve welfare and reduce the spread of invasive species.

The prior literature greatly informs the socially optimal management of invader spread, but provides less insight into decentralized responses to invasive species spread. Researchers have used spatial optimal control models to study socially optimal invasive species control programs (Epanchin-Niell and Wilen 2012; Homans and Horie 2011; Potapov et al. 2007; Sharov and Liebhold 1998; Sims and Finnoff 2012). These studies have focus on common property such as public forests (e.g., Sims et al. 2010; Sims and Finnoff 2012) and aquatic systems (Lovell et al. 2006). Prior research also emphasized the biophysical processes of spatial diffusion (e.g., Gaff et al. 2007; Homans and Horie 2011; Horan et al. 2005; Potapov 2009; Potapov et al. 2007; Sanchirico and Wilen 1999; Sharov 2004; Smith et al. 2009a), the role of biophysical spatial heterogeneity (Epanchin-Niell and Wilen 2012), and the interaction between space and uncertainty (Sims and Finnoff 2012). Social planner problems commonly are contrasted with invasions taking place in the commons. However, if invasive species alter areas that are managed as commons, then there are likely few economic losses from the invasion, because intertemporal externalities dissipate rents through unregulated access (Knowler 2005).

Our results suggest that the current property value (i.e. the value at risk) is central to the cost of the externality. The model predicts that, all else equal, managers of more valuable properties will be less tolerant towards and more aggressively control pests. We predict that when the pest population grows faster, the expected immigration rate is greater, and insecticide is less effective, property managers spray less frequently and tolerate larger pest populations. Results related to the immigration rate, which captures geographic distance, parcel size, and the expected (or known) behavior of others, are important. High rates of connectivity, via the immigration rate, limit the property manager's ability to exclude undesirable processes, attenuate property rights, and result in a greater proportion of the externality being transferred to neighbors, thereby eroding property value and the private incentives for pest control.

We contribute to the literature in three ways. First, we provide a model that captures key features of invader spread on private property. Second, we illustrate the potential for Coasian exchange (Coase 1960) to reduce invasive species spread. In so doing, we identify a link between the weaker link problem (Cornes 1993) and strategic complements (Bowles 2004). Furthermore, we follow Warziniack et al. (2011) is clearly identifying the invasive species problem as one of jointness of supply and shiftable externalities (Bird 1987; Geaun 1993; Hansen 2002). Third, we find the counter-intuitive result that applying a Pigouvian tax directly to the source of “biological pollution” can potentially provide an incentive for behaviors that increase the number of insects that migrate to others' property. Taxes can have adverse effects because a Pigouvian tax reduces the value of and incentive to maintain productive capital. Moreover, because the insect “pollution” is self-renewing, driving the

least profitable producers to abandon production might exacerbate invasion, if exit causes a non-trivial delay in the liquidation of pest habitat. This may be the case for fast growing and spreading pests during periods of macroeconomic contraction or cyclical downturns in the industry.

## 2. Methods and Theory

### 2.1 Motivating example

This paper is motivated by the invasive insect pest Asian citrus psyllid (ACP), which damages citrus trees and vectors citrus greening disease, also called Huanglongbing (HLB). ACPs have been detected in Florida, Texas, Arizona, and California, placing the US citrus industry at risk (Gottwald 2010).<sup>4</sup> California is the most recent state to report a substantial invasion by ACPs. As of 2009 citrus represented \$1.8 billion in cash receipts and \$3.0 billion in total economic activity in California (Richards 2009). This, coupled with the importance of California to the US fresh citrus market, suggests substantial scope for welfare loss.<sup>5</sup>

Joint models of ACP, HLB, and citrus are complex. What have been described as “simple” models require 10 or more state variables with non-autonomous dynamics (Chiyaka et al. 2012). Rather than become lost in the details of ecological modeling, we focus on the stylized facts from the system to advance our main goal of understanding the interaction among the forward looking management incentives generated by spatially bounded private property, the invasion process, and market-based mechanisms for invasive species control. There are five facts that shape our model. First, ACP are highly fecund, and once in a grove an untreated population grows quickly (Halbert and Manjunath 2004). Second, ACPs are poor fliers and remain in their “home” orchard, but may disperse with wind assistance or when disturbed (Hall 2011; Van den Berg et al. 1991). Therefore, the dispersal process may be best modeled as density independent. Third, ACPs are attracted to and damage new citrus growth and the fruit bearing parts of the tree, but adult ACPs may be supported on mature leaves and alternative host plants (Chiyaka et al. 2012; Halbert and Manjunath 2004). Trees can support large numbers of ACPs, with some studies reporting over 40,000 ACPs/tree (Halbert and Manjunath 2004) and 200 insects per m<sup>2</sup> (Aubert and Quilici 1987). Fourth, the ACP-HLB virus is complex, but is strongly associated with ACPs (Halbert and Manjunath 2004). When ACPs vector HLB, the ACP-HLB complex is capable of killing trees before they reach fruit producing age of 4–8 years (Halbert and Manjunath 2004; O’Connell et al. 2009). Fifth, the chemical treatments found most effective at killing and controlling ACPs, e.g., neonicotinoids and pyrethroids, are applied on a per acre bases at per acre cost (Grafton-Cardwell pers.com.). It is unlikely that the number of insects or condition of trees influences the per acre treatment intensity.

### 2.2 The model

We consider the ACP control problem from the standpoint of a property manager. Each manager has secure rights to a patch of the landscape, but ACP dispersal connects patches.

<sup>4</sup>Brazil and China have also suffered from the spread of ACP-HLB.

<sup>5</sup><http://usda.mannlib.cornell.edu/MannUsda/viewDocumentInfo.do?documentID=1377>

Managers cannot directly control the ACP dispersal process. Prior publications assume a social planner and continuous control choices for invasive species (e.g., Eiswerth and Johnson 2002; Finnoff et al. 2007; Leung et al. 2005). Fenichel et al. (2010) allow for a continuous control of a disease carrying insect vector, but find that a single pulse control is optimal in a finite time horizon problem suggesting that repeated pulse controls may be optimal over longer planning horizons. Saphores (2000) models control choices as time between spraying treatments of a fixed size and cost.<sup>6</sup> We adopt a similar approach, and consider spraying as a repeat optimal stopping problem with a flow of net benefits between stopping times (Couture and Reynaud 2011; Hartman 1976).

We assume that a citrus grower, who manages a fixed acreage, gains net revenue from citrus operations as a function of the standing crop of citrus capital (i.e., trees),  $k$ , and has the option to spray crops in order to reduce insect load at a fixed cost per spraying event. This is isomorphic to an impulse control problem or rotation problem where the length of rotation changes as the state of the system changes. The result is a closed-loop spraying feedback strategy.<sup>7</sup> Furthermore, we assume that instantaneous net revenue, when spraying is not undertaken, is  $f(k(t))$ , and that  $k(0)$  is the optimal amount of citrus capital for the grower to hold in a pest free environment.<sup>8</sup> Furthermore, we assume that ACPs never provide a pruning service that keeps trees at the optimal size. This is because ACPs the primarily vector HLB, stunt leaf growth, and deposit honey dew on new growth. If prices, non-pest management costs, and citrus levels were fixed, then in the absence of an insect pest the net present value of the grower's citrus production is  $f(k(0))/\rho$ , where  $\rho$  is the discount rate.

When insects,  $x$ , are present, and spraying does not occur, ACP growth increases weakly in the citrus stock,  $\dot{x}/k > 0$ . The marginal effect of citrus on the growth of the insect population is weakly positive because citrus provide habitat for ACP, but may not be the limiting resource for insect population. Insects may immigrate to the citrus grove from outside. Immigration is assumed to be independent of the number of current insects in the grove and the decision to spray. While this may be a strong assumption for some species, it is descriptive for ACPs. They are poor fliers and wind dispersed or introduced on human equipment and nursery stock.<sup>9</sup> We assume that ACPs damage citrus capital according to a predation function where  $k/x < 0$ .

The grower can choose to spray his crop with an insecticide that kills a proportion of the invading insects. If the grower never sprays, then the present value of the citrus stock conditional on biological dynamics is  $\int_t^\infty f(k(t))e^{-\rho(s-t)} ds$ . This may be thought of as a scrap value that comes from a process of gradual abandonment.<sup>10</sup> In Florida and China whole areas of citrus production have been abandoned because of ACP and HLB (Aubert

<sup>6</sup>Marten and Moore (2011) allows chemical and bio- control and allows for variation in intensity to assess socially optimal management (since bio-control interventions are seldom done by a single landowner). Sims et al. (2010), and Sims and Finnoff (2012) investigate control of stochastic spread of forest damaging insects.

<sup>7</sup>One advantage of this approach is that in principle it enables the analyst to consider the case of zero insects as a special case of the feedback rule thereby bridging localized control and localized prevention, and avoiding the need to frame the prevention-control question as one of switching regimes (Mehta et al. 2007; Polasky 2010). We do not exploit this property of this setup in the current research, and this extension is left for future work.

<sup>8</sup>This assumption implies that the bio-physical and economic environments have been relatively stable such that the grower has been able to converge to a long-run equilibrium.

<sup>9</sup>We do not consider grove biosecurity, which could affect the introduction of new insects.

1992; Morris et al. 2008). The USDA reports 131–139 thousand acres of abandoned citrus groves in Florida between 2010–2012, with an additional 5 thousand acres of, “abandoned, unintentional, or feral citrus trees scattered under their [other forest areas] canopy...[that]... pose a potential threat as a possible source of pests and diseases.”<sup>11</sup> In our numerical analysis we also consider alternative fixed scrap values that do not depend on the current state of the system.

The growth of the ACP stock leads to a non-constant citrus capital depreciation rate. The grower’s problem is to maintain capital by managing the ACP stock, which affects the depreciation rate. The grower can reset the depreciation rate of the citrus stock by spraying the insects.<sup>12</sup> In a capital theoretic sense, spraying is an investment in citrus capital asset maintenance. The effectiveness of insecticides is often reported as a percent. For example Setamou et al. (2010) report a 90% efficiency of an ACP targeted pesticide. We consider a spraying control with a fixed effectiveness of  $1 - a$  and no environmental persistence.<sup>13</sup>

Assume that the grower chooses a spraying strategy to maximize the net present value of his citrus grove over an infinite planning horizon. This requires the grower to consider future spraying intervals in addition to the current interval making the problem one of repeat optimal stopping, where the “rotation” length is also a function of the amount of citrus stock held. The optimal spraying interval from any time period, defined from  $t$  to  $\tau$ , must satisfy the Bellman’s equation

$$V(k(t), x(t)) = \max_{\tau} \left\{ \int_t^{\tau} f(k(s)) e^{-\rho(s-t)} ds + \mathbb{E} \left( e^{-\rho\tau} (V(k(\tau), \alpha x(\tau)) - c) \right) \right\} \quad (1)$$

where  $\mathbb{E}$  is the expectation operator,  $c$  is the cost of spraying incurred after  $\tau$  time steps.

Market-based controls, policies designed to change the incentives for control without mandating action, directly alter, in a predetermined fashion, the value of  $c$  that a grower experiences, thereby changing a grower’s behavior. However, market-based policies also alter the behavior of neighboring growers, which influences the growth of the ACP population on the own grower’s property through the ACP immigration rate.

Spraying optimally occurs when the value matching condition

$$V(k^*, x^*) = V(k^*, x^0) - c \quad (2)$$

<sup>10</sup>Morris et al. (2008) write, “some [growers] know they have greening [HLB] but rather than institute control practices, plan to take whatever profits can be made, then replant [with an alternative crop] or sell the land.”

<sup>11</sup>[http://www.nass.usda.gov/Statistics\\_by\\_State/Florida/Publications/Citrus/aban/CitAA12.pdf](http://www.nass.usda.gov/Statistics_by_State/Florida/Publications/Citrus/aban/CitAA12.pdf)

<sup>12</sup>Smith et al. (2009b) use a similar setup to model the management of the depreciation of property values associated with beach erosion through beach nourishment using an approach following Hartman (1976). A critical difference between Smith et al. (2009b) and ours study is that Smith et al. (2009b) always reset the beach to the same width, while in our problem a proportion of insects are killed so the post spraying level of insects depends on the pre-spraying population.

<sup>13</sup>Environmental persistence of pesticide could increase the incentives for spraying. Including environmental persistence adds another state variable with nonlinear dynamics to the model. While important for considering for prescriptive purposes, residual pesticide effects likely will not affect our core insights, and would make graphical visualization challenging.

is satisfied (Dixit and Pindyck 1994; Miranda and Fackler 2002), where  $x^0$  is the size of the insect population immediately following spraying. The value matching condition says that the optimal value prior to spraying equals the optimal value following spraying less the cost of spraying. If  $x^0$  is fixed and known, as in Smith et al. (2009b), then solving the final spraying state condition is a matter of solving for pairs of insects and capital that may be experienced in the final spraying period. However, under the more biologically realistic assumption that spraying has a technical efficiency of  $(1 - \alpha)$ , as in Saphores (2000), then Eq (2) is more precisely specified as

$$V(k^*, x^*) = V(k^*, \alpha x^*) - c \quad (3)$$

which can be rewritten as

$$V(k^*, x^*) - V(k^*, \alpha x^*) + c = 0. \quad (3')$$

Additionally, the smooth pasting condition requires the marginal cost of an insect to be equal before and after spraying (Dixit and Pindyck 1994; Miranda and Fackler 2002)

$$V_x(k^*, x^*) - V_x(k^*, \alpha x^*) = 0 \quad (4)$$

There are two dynamic stocks,  $x(t)$  and  $k(t)$ , but only the equation of motion associated with  $x$  provides a smooth pasting condition (see Saphores 2000 for a similar observation).

$$A = V_k(k^*, x^*) - V_k(k^*, \alpha x^*) < 0 \quad (5)$$

Unlike the smooth pasting condition shown in Eq (4), Eq (5) must be negative because the control does not directly affect  $k$ . The intuition for this is provided by considering two capital stocks identical in every way except for their depreciation rates. The stock with the lower depreciation rate is more valuable, *ceteris paribus*. Increased insects increase the depreciation rate of citrus capital.  $V_k$  is the shadow value of citrus capital, and  $x^0 = \alpha x^* < x^*$ , so there is no smooth pasting condition associated with citrus capital.

The value matching and smooth pasting conditions jointly define a stopping boundary that divides the state space into two regions. The region of state space where it is optimal to tolerate pests and delay spraying is the waiting region, generically called the continuation region. In the continuation region the marginal benefit of spraying is not great enough to offset the marginal cost. The other region of state space is the spraying region, generically called the stopping region. As soon as the stopping region is entered, it is optimal to spray and to remove a portion of the insect population. The optimal feedback rule is defined in state space as the boundary between the continuation and stopping regions. If  $V$  were known, then Eq (3) and Eq (7) would fully identify the boundary of the waiting region. However,  $V$  is an unknown and must be solved for. We find it useful to juxtapose analytical and numerical results. Therefore, we introduce our numerical methods before proceeding to analysis of the model.

## 2.3 Numerical Methods

Assuming  $V$  is continuous it can be arbitrarily approximated with polynomials, and approximation theory suggests that Chebychev polynomials can provide good approximations to value functions (Adda and Cooper 2003; Miranda and Fackler 2002; Vlassenbroeck and Van Dooren 1988). We approximate the value function using Chebychev polynomials at a finite number of  $(k, x)$  pairs called collocation nodes. Following Miranda and Fackler (2002), we define the multidimensional Chebychev polynomial as the Kronecker product of  $n^{\text{th}}$ -order unidimensional Chebychev polynomials.

With the value function approximated as a Chebychev polynomial we follow Balikcioglu et al. (2011) and Marten and Moore (2011) to recover the coefficients of the approximating polynomial and place each node in the stopping (spraying) or continuation (waiting) region. The approach taken by Balikcioglu, Fackler, and Pindyck (2011) and Marten and Moore (2011), referred to as BFP-MM, is elegant because it makes direct use of the Hamilton-Bellman-Jacobi identity and intuitive boundary conditions.

The BFP-MM approach uses the inequality

$$\rho V(k, x) - H \geq 0 \quad (6)$$

where  $H$  is the current value Hamiltonian,  $H = f(k, x) + V_k \dot{k} + V_x \dot{x}$ , and Eq (6) holds as an equality so long as spraying may occur at any future instant. Next, observe that

$$V(k, x) = \int_t^\infty f(k(s)) e^{-\rho(s-t)} ds \geq 0 \quad (7)$$

conditional on ACP and citrus dynamics, because never spraying provides a lower bound on the optimal value of the value function. The second term in (7) is the scrap value. In our numerical analysis we also consider alternative scrap values that are invariant to the state of citrus stock, representing alternative land use. Finally, if

$$V(k, x) - [V(k, \alpha x) - c] \geq 0 \quad (8)$$

is not strictly positive, then spraying occurs. When (8) holds as a strict equality it is the value matching condition.

The minimum of (6)–(8) must hold as a strict equality at each collocation node.

$$\text{Min}\{\rho V(k, x) - H, V(k, x) - \int_t^\infty f(k(s)) e^{-\rho(s-t)} ds, V(k, x) - [V(k, \alpha x) - c]\} = 0 \quad (9)$$

Standard numerical minimization procedures are capable of solving for the coefficients of the approximating polynomial (Balikcioglu et al. 2011; Marten and Moore 2011).<sup>14</sup>

<sup>14</sup>While Eq (9) can be implemented directly, rewriting the expression in terms of basis functions and employing an alternative, but smoother, function with the same roots, such as the Fischer-Burmeister function (Sun and Qi 1999), enhances numerical convergence and reduces memory requirements. We are grateful for this recommendation from an anonymous reviewer.



In order to map out the stopping boundary we specify  $35 \times 35 = 1,225$  collocation nodes generated as the zeros of a two-dimensional, 35<sup>th</sup> order Chebychev polynomial in the domains  $x \in [2,500]$  and  $k \in [0.25,1]$ . Greater density of nodes did not qualitatively change results and slowed computation. We used a 16<sup>th</sup> order two-dimensional Chebychev polynomial to approximate the value function. Increasing the approximation order did not alter the results, but slowed computation time. Numerical solvers were used to find a set of polynomial coefficients that best satisfy Eq (9). Mathematica 9.0 (Wolfram) was used to write out each polynomial, keep track of the associated derivatives, and numerically minimize the minimands.

## 2.4 Functional specification

Our numerical technique requires that we specify functional forms for the grower's instantaneous profit function,  $f(k) = qk$ , and the biological dynamics. We assume that perennial citrus crop capital is lost according to

$$\dot{k} = G(k) - \beta x k = gk \left( 1 - \left( \frac{k}{k(0)} \right)^\theta \right) - \beta x k \quad (10)$$

$G$  is a citrus replacement function that represents citrus regrowth. Given the high growth rates and fast acting damage that ACPs and HLB cause and experience in Florida, China, and Brazil, for our base case we assume that citrus cannot self-regenerate on a time scale relevant for our analysis and that citrus is irreversibly lost, i.e.,  $G = 0$ . In our uncertainty analysis we allow citrus to be replaced either naturally or through grower actions. Our specification for  $G$  allows recovery at a near constant proportional rate of  $g$  up to full recovery at the level of  $k(0)$  if  $\theta$  is large. In our numerical simulations we set  $\theta = 100$ . This implies that proportional citrus growth rate falls to 95% of  $g$  when the citrus stock reaches  $0.97k(0)$ . We interpret this rapid rate of recovery as the best case scenario for citrus regrowth, and assume it is achieved at zero cost.

$\beta$  is the feeding rate of insects on citrus. We take the feeding rate to encompass damage caused by HLB in addition to direct feeding damage, thereby avoiding being mired in the ecological details of the complex ACP-HLB-citrus system (see Chiyaka et al. 2012 for an example of efforts to model this ecological system). Eq (10) can be interpreted as the grower having an initial endowment of citrus capital that depreciates at the rate  $\beta x(t)$ . The invading insects depreciate the citrus stock at a rate proportional to the insect population,  $x$ .

A common specification of host-macroparasite models is

$$\dot{x} = rx \left( 1 - \frac{x}{bk} \right) + \varepsilon \quad (11)$$

where  $r$  is the parasite's intrinsic growth rate,  $k$  is the host population that provides carrying capacity for the parasite,  $b$  is the maximum number of parasites (ACPs) that a host (citrus grove) can support, and  $\varepsilon$  is the expected exogenous amount of immigration per instant (Roberts et al. 1995).

Table 1 presents parameters used in the numerical simulations. These parameters were chosen to be realistic and to facilitate numerical convergence. The choice of parameter values is explained in the appendix.

### 3. Results

We use a mix of analytical and numerical analysis to illustrate the qualitative properties of a grower's spraying rule, the growers' responses to market based interventions, and the behavior of other growers. These results build intuition about the incentives that a grower faces.

#### 3.1 The grower's stopping boundary

The location and behavior of the stopping boundary in state space ( $k$ - $x$  space) summarizes a grower's reaction to changing conditions. Consider the relationship between  $k^*$  and  $x^*$ . Intuition suggests that the stopping boundary is downward sloping in  $k$ - $x$  space so that growers make spraying investments at lower insect levels as the value of citrus assets increases.

Using the parameterization in Table 1, we solve for the grower's decision boundary in  $k$ - $x$  space. The optimized value function in  $k$ - $x$  space is shown in Fig 1, with light shades indicating greater values. The value of the optimized value function is increasing in citrus stock and decreasing in ACPs. The average residual error per collocation node is  $8.7 \times 10^{-4}$ . The black dots in Fig 2 plot the region where spraying is optimal (collocation nodes in the waiting region are shown in gray). The lower edge of this region is the optimal stopping boundary during the invasion process, and it is downward sloping in state space.

To explore what generally must be true for the stopping boundary to be downward sloping in  $k$ - $x$  space set Eq (3') equal to Eq (4) and totally differentiate (Dixit and Pindyck 1994)

$$[V_{k^*}(k^*, x^*) - V_{k^*}(k^*, \alpha x^*)]dk^* + [V_{x^*}(k^*, x^*) - \alpha V_{x^*}(k^*, \alpha x^*)]dx^* = [V_{xk^*}(k^*, x^*) - V_{xk^*}(k^*, \alpha x^*)]dk^* + [V_{xx^*}(k^*, x^*) - \alpha V_{xx^*}(k^*, \alpha x^*)]dx^* \quad (12)$$

To reduce notation write Eq (12) as  $Adk^* + Bdx^* = Cdk^* + Ddx^*$ . The slope of the stopping region boundary is,

$$\frac{A-C}{D-B} \frac{dx^*}{dk^*}. \quad (13)$$

$A - C$  and  $D - B$  must have opposite signs for the slope of the stopping boundary to be negative. Eq (5) establishes that  $A < 0$ . From Eq (4),  $C = 0$ , making the numerator of Eq (12) negative. Eq (4) requires  $V_x(k^*, x^*) = V_x(k^*, \alpha x^*)$ , therefore  $V_{x^*}(k^*, x^*) < \alpha V_{x^*}(k^*, \alpha x^*)$  because  $V_x < 0$  and  $\alpha \in (0, 1)$ , making  $B < 0$ . The left-hand-side (LHS) of Eq (12) is negative; so, by equivalency, the right-hand-side (RHS) is negative.  $D < 0$  because  $V_{xx^*}(k^*, x^*) < 0$ , which must also hold to satisfy the second order sufficiency conditions for a maximum, and  $V_{xx^*}(k^*, \alpha x^*) > 0$ . The sign of the numerator is clear, but because both  $D$  and  $B$  are negative, there are two potential cases for the denominator:  $D > B$  and  $D < B$ . First, if

$D > B$ , then the stopping boundary is downward sloping. Conversely, if  $D = B$ , then the stopping boundary must not be downward sloping. The numerical results and intuition suggest that for spraying to be optimal at a point in time or in the future, then  $D > B$ . Once the case  $D = B$  is reached it is optimal to abandon the grove. This says for spraying to be privately optimal, the marginal losses averted from retarding the ACP population must exceed marginal losses from the ACP population itself. In other words, it is optimal to spray when delaying spraying transfers a larger cost to one's self in the future than the current cost of spraying.

The downward sloping nature of the stopping boundary in  $k$ - $x$  space implies that the size of the citrus stock and the value at risk matter (see Perrings et al. (2010) for empirical evidence of similar findings with respect to invasive disease prevention). All else equal, the more citrus capital lost the more insects that will be tolerated. If the grower exists in a landscape with other growers, and the number of insects emitted to other groves is proportional to the number of insects on the grower's grove, then forgone abatement transfers more pests to neighbors – a spatial externality. Moreover, the size of the externality generated by an individual grower is not solely dependent on the insects emitted – the size of the externality depends on the crops elsewhere available for damage, potentially the history of damage to those crops, and the reaction of other growers (Shaw and Shaw 1991). Intuition and the numerical results suggest that early in an invasion  $D > B$ , but that it is possible for the invasion to progress so that  $D = B$ , which defines a threshold for not spraying in the future. Once this threshold is crossed the grove continues to emit insects unless citrus are removed. It may be optimal for the grower to continue harvesting citrus for a period before either abandoning completely or repurposing the land.<sup>15</sup>

### 3.2 Comparative statics and a grower's spraying region boundary

To analyze the influence of market-based mechanisms on private incentives for invasive species control it is important to understand how changes in cost,  $c$ , and the expected number of new invaders per unit time,  $\varepsilon$ , affect the location of the stopping region boundary in state space. The size of the waiting region bounds the potentially privately tolerable states of the world. In the waiting region, a grower does not have sufficient private incentives to engage in spraying. Conversely, in the spraying region, above the stopping boundary, a grower has sufficient private incentives to engage in pest control that derive from his right to future use of the citrus capital. In the spraying region, no public intervention is needed to induce pest control behaviors. A spatial externality exists if a neighbor would be willing to pay the grower to be less tolerant of insects so that the grower's stopping boundary shifts downward in state space.

Our general strategy for analyzing the effect of changes in  $\varepsilon$  and  $c$  on the location of the boundary is to implicitly differentiate Eq (3') to find the change in  $x^*$  and  $k^*$  with respect to the parameters of interest.

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<sup>15</sup>If growers think a cure might be available in the future they may "moth ball" their groves and cease active management, but this does not stop the groves from producing insects.

**Proposition 1**—Increases (decreases) in spraying costs shift the stopping boundary up (down), increasing (decreasing) the size of the waiting region. An increase (decrease) in spraying cost shifts the stopping boundary right (left), increasing (decreasing) the size of the waiting region.

Implicitly differentiate Eq (3') and asserting that Eq (4) holds, yields  $\frac{dx^*}{dc} = -B^{-1} > 0$  and  $\frac{dk^*}{dc} = -A^{-1} > 0$ .

This analytical result is verified with numerical sensitivity analysis (Fig 3). Increases in spraying costs reduce the size of the spraying region, consistent with the stopping boundary being downward sloping in state space. High spraying costs make it more expensive to protect the underlying capital asset and reduce the incentives to spray. Policy makers could exploit the incentives generated by private property to induce more aggressive invader control by reducing the cost of spraying, *ceteris paribus*. Such a policy that effectively compensated growers from abating insect pests would align with the literature on effective policies for addressing shiftable externalities (Bird 1987; Geaun 1993).

The technical efficiency of the treatment has an ambiguous effect on the size of the waiting region, and therefore it is not clear how investments in improved spraying technology affect the incentive to spray. Increasing technical efficiency effectively lowers the cost of control. Note that the technical efficiency of the treatment is  $1 - \alpha$ , and implicitly differentiating (3')

$\frac{dx^*}{d\alpha} = \frac{x^* V_x^*}{V_{x^*}(k^*, x^*) - \alpha V_{x^*}(k^*, \alpha x^*)} > 0$ . However, increased technical efficiency also enables

the grower to delay longer between sprayings,  $\frac{dk^*}{d\alpha} = \frac{x^* V_k^*}{A} < 0$ . Our numerical analysis suggests that the cost-savings effect cause the boundary to shift downward with increasing technical efficiency dominates (Fig 3), suggesting public investment in spraying efficiency could be beneficial. But our numerical analysis also suggests longer wait times between spraying indicated by the contraction of the spraying region from above and left. These results are dependent on parameter values, so the policy conclusion is an empirical question.

Biological parameters  $r$  and  $\varepsilon$  generally reduce the size of the stopping region. The smooth pasting condition (4) requires the payoff function prior to spraying and value function following spraying to meet at a tangent. However, by continuity the value matching condition, (3') establishes the neighborhood where the payoff function prior to spraying and value function post spraying meet. Implicitly differentiating (3'), but enforcing that Eq (4) holds with equality reveals that the boundary of the continuation region moves along the

level-set of candidate thresholds,  $\frac{dx^*}{d\gamma} = -\frac{Ak_\gamma^*}{2B}$ ; a vertical increase yields a horizontal decrease where  $\gamma \in \{r, \varepsilon\}$ . This does not tell us the direction of the shift in the stopping boundary. However, the economic intuition that led us to believe that the boundary of the waiting region is downward sloping, leads us to hypothesize that an increase in any of the biological parameters leads to a smaller spraying region. Greater values of  $r$  or  $\varepsilon$  cause the system to travel northwest faster. Furthermore,  $V_\varepsilon(k, x) = V_k k_\varepsilon + V_x x_\varepsilon < 0$ , which follows

from the definitions of  $V_k$ ,  $V_x$ , Eq (10), and Eq (12). Similar results can be derived for  $V_r(k, x) < 0$ . A grower would prefer a lower rate of invasion and a slower growing pest because increases in the biological parameters  $r$ , and  $\varepsilon$  lead to lower valued capital. Numerical sensitivity analysis supports this intuition (Fig 3).

The parameter  $\beta$  represents the damage inflicted by ACPs on citrus. Increases in  $\beta$  do not affect the growth rate of the ACP population, but increases in  $\beta$  lead to greater citrus damage at lower ACP populations. This leads growers to spray at lower ACP levels (Fig 3).<sup>16</sup> However, the high rates of damage also cause citrus to lose value faster, which leads spraying region to contract from the left and above (Fig 3). The parameter  $b$  represents the dependence of ACPs on citrus and can be thought of as the carrying capacity that a unit of citrus provides ACPs. Our numerical sensitivity analysis suggests that an increase in  $b$  shifts the spraying boundary downward. However, increases in  $b$  also allow the ACP population to get larger, leading the grower to give up on spraying at lower pest levels or greater citrus levels. This causes the spraying region to contract from the northwest (Fig 3).

Next, we consider the potential for citrus regeneration. These results can either be interpreted as natural regeneration of citrus or grower enhancements, which are costless in our analysis. We consider the possibility of 10 and 25 percent regeneration per year. When citrus can regenerate, the stock becomes more valuable, enlarging the spraying region (Fig 3). The spraying boundary remains downward sloping. If the grower had to incur a cost to achieve increased growth, then, assuming it is optimal for the grower to incur a cost to enhance growth, the results would look qualitatively similar – the spraying boundary would be downward sloping, and the grower sprays over a large area of state space to protect the more valuable asset. If the grower were to choose to reduce citrus stock in response to ACP, this could be represented as a leftward shift in state space.

In our base case model the scrap value is gradual abandonment of the grove. The grower continues to harvest the valuable fruit and gains value until fruit production ceases, but stops engaging in control. However, other land use can potentially have greater value than a diminishing citrus grove. We substitute fixed scrap values. A fixed scrap value decreases the value of spraying, but this does not mean that it is optimal for the grower to sell immediately. The grower still holds the grove for a period of time, gaining citrus net revenue and producing ACPs, and then sells at the state invariant price. If the fixed scrap value is great enough, then the grower has no incentive to spray, but may have an incentive to delay slightly before taking the payout for “selling” the land.

### 3.3 The potential for a market-based mechanism for invasive insect control

We now use the insight from the prior sections to consider the potential for market-based mechanisms to exhaust Paerto improving exchanges. The section makes two contributions. First, it puts spatial externalities in the context of spatially delineated property rights, and makes explicit the observation that geographic space is an observable risk factor associated with real estate. Second, it links the literature on transferable and spatial externalities. In the

<sup>16</sup>A 10% increase in  $\beta$  did not have an observable influence on the boundary given the density of collocation nodes. Fig 3 presents a doubling of  $\beta$  for illustrative purposes.

case where all geographic space corresponds to private property, a dynamic Coase-like solution seems feasible (Coase 1960).

Consider two growers,  $i$  and  $j$ , with secure property rights to citrus, but without clarified responsibilities for ACPs. Modify Eq (12) to

$$\dot{x}_i = rx_i \left( 1 - \frac{x_i}{bk_i} \right) + \varepsilon(x_j; d) \text{ and } i \neq j \quad (14)$$

Eq (14) says that the expected number of immigrant insects into patch  $i$  is a function of the number of insects in patch  $j$ , and we assume that  $\varepsilon_{x_j}(x_j; d) > 0$ . The parameter  $d$  is included in Eq (14) to indicate geographic distance; all else equal  $\varepsilon_d(x_j; d) < 0$ . Growers spray to maximize the net present value of their own privately held citrus, but do not consider the additional benefits that spraying confers to other patches by reducing sources of invading insects.

All else equal, reducing immigrant pests increases the value of the citrus stock. Our results above suggest that increasing value increases incentives to invest in protection. Gramig and Horan (2011) similarly show that higher rates of infection lower the incentives for biosecurity investments in livestock.<sup>17</sup> Our comparative static results can be interpreted as defining a forward-looking grower's best reaction curve to cost and invasion rate changes. When grower  $i$  sprays he provides incentives for grower  $j$  to spray by reducing the growth rate of  $j$ 's pest population. However, grower  $j$  may spray less than would be optimal for grower  $i$ . A payment from grower  $i$  to grower  $j$  to reduce grower  $j$ 's spraying costs may be a Pareto improving exchange and corresponds to a Coasian solution. For grower  $i$  to make a payment to grower  $j$  to reduce insect emissions, grower  $i$  must be able to improve his lot when grower  $j$  maintains  $x_j$  at a level lower than is privately optimal for grower  $j$  in the absence of payment.

Consider the simplified case when grower  $i$  can only make payments to grower  $j$  at the time that grower  $i$  sprays, and the payment is held in escrow until grower  $j$  sprays. Grower  $j$  knows that he will receive this payment at the time of spraying. This assumption allows us to consider the compensation paid to grower  $j$  as an increase in the spraying costs of grower  $i$ .<sup>18</sup> A payment,  $p$ , has two effects on grower  $i$ 's value function. The direct effect,  $V_p < 0$ , which increases the cost of spraying. The second effect is an indirect effect through a reduction in insect immigrants  $V_{\varepsilon(x_j)} \varepsilon(x_j)_p > 0$ . The grower follows an equi-marginal principle and voluntarily chooses  $p$  so that direct effect exactly offsets the indirect effect.

The payment increases flexibility for grower  $i$  in two ways. First, if grower  $i$  has the ability to make a payment to grower  $j$ , which may cover only part of  $j$ 's cost of spraying, makes

<sup>17</sup>Moving grower  $j$  farther from grower  $i$ , which is essentially what biosecurity measures do, enhances the value of grower  $i$ 's capital, but investments in biosecurity may have different properties than investments in onsite control. Biosecurity may also transfer or shift the externality to neighbors.

<sup>18</sup>This simplifies the problem by eliminating the problem of the optimal time to pay. The La Chatelier principle suggests that if it is optimal for grower  $i$  to make a payment at the appointed time, then freeing the time of the payment can make grower  $i$  no worse off. For the payment to be moved voluntarily to another time, the payment can also not make grower  $j$  worse off. Therefore, a more flexible program would only enhance the likelihood that a payment system is welfare enhancing.

grower  $i$ 's marginal cost of spraying continuous rather than discrete. The grower can choose to incur greater spraying costs for greater insect reductions without incurring the cost of an entire additional spraying event. Second, the payments provide a control variable that reduces infestation from a previously uncontrolled source with respect to grower  $i$ 's choices.

The payment itself must shift grower  $i$ 's stopping boundary up in accordance with proposition 1. The direct effect of making the payment reduces grower  $i$ 's incentive for control. If grower  $i$  voluntarily incurs greater spraying costs to reduce  $j$ 's spraying cost this shifts grower  $j$ 's stopping boundary downward. This payment reduces the privately optimal tolerable insect level for grower  $j$ . For the payment to be voluntary, the indirect effect of reduced insect invasion must at least fully offset the cost effect so that the net effect is that grower  $i$ 's waiting region does not increase. Therefore, the total effect on grower  $i$  cannot decrease the incentive for engaging in control. Numerical sensitivity analysis suggests that immigration of insects from outside the grove shifts the stopping boundary up and to the right (Fig 3).

Morris et al. (2008) observe that “growers believe that because their neighbor is not controlling [citrus] greening [HLB] their efforts [to control ACP and HLB] would be futile.” Morris's observation suggests that growers fear having pests transferred to them. Our model predicts that spraying to prevent growth of pests is a strategic complement (Bowles 2004). Spraying generally has significant benefits to the grower himself, as well as to his neighbors. Spraying abates the actual externality rather than transferring it to neighbors or to one's future self (Bird 1987). If grower  $i$  experiences an exogenous change in condition so that grower  $i$ 's boundary shifts downward and grower  $j$  sprays sooner, then this decreases the expected number of insects that grower  $i$  exports to grower  $j$ , increasing the value of grower  $j$ 's citrus stock. The lower immigration rate leads grower  $j$  to shift his stopping boundary in the same direction as grower  $i$ . This strategic complementary effect occurs because the dominant concern is the potential intertemporal transfer of ACP to himself, and fully eliminating the immigration effect does not alleviate the need to control the internal growth of the ACP stock.<sup>19</sup> Reducing immigration provides greater incentives for control of the internal growth of ACP because the control is more effective. If the landscape is covered with private property, then it might be possible to rely on private property rights and a series of exchanges to control invaders.

### 3.4 Endogenous weaker link strength

Consider the case when grower  $i$  and  $j$  are identical in every way, including that  $k_i(0) = k_j(0)$ . The growers' patches are invaded by the same number of insects at the same time, and insects disperse in a reciprocal fashion. This unrealistic case provides intuition to the potential role for a market because it forces homogeneity between growers. In this case, the Nash equilibrium is for synchronous spraying with identical stopping boundaries. This follows from the assumption of perfect homogeneity. The result is unaffected by the number of growers as long as strict homogeneity is enforced.<sup>20</sup> Indeed, assuming that no insects die

<sup>19</sup>Biosecurity investments that prevent transmission between groves could be a strategic substitute that leads to free-riding. Other research on invasive species prevention and control suggests that actions to prevent invasion may shift risk to others (Warziniack et al. 2011), but spraying abate damages rather than shifting them.

during dispersal, the grower can effectively ignore the “trade” in insects because it is perfectly balanced – in effect separating the system. Grower  $i$  has no incentive to allow insects to increase, nor could grower  $j$  compensate him to increase spraying and reduce insects without making himself worse off. Heterogeneity that conveys local information is required for there to be a meaningful spatial externality (Xepapadeas 2010).

The degree to which a weaker link good is under provided depends on heterogeneity in exogenous factors such as preferences and incomes (Cornes 1993). Two sources of heterogeneity are likely to be present: preference or profitability heterogeneity, which we take as exogenous, and system state heterogeneity, which is at least partially endogenous. Preference or profitability heterogeneity implies that  $f_i(k_i(t))|_{x_i(t)} \neq f_j(k_j(t))|_{x_j(t)}$ , even if  $k_i(t) = k_j(t)$  and  $x_i(t) = x_j(t)$ . This could follow from the realistic case of differentiated crops selling into differentiated product markets, heterogeneity in land fertility, or management skill. Alternatively, fixed capital could also create profitability heterogeneity. In the case of citrus, differences likely exist between commercial producers and owners of ornamental citrus.

Spatial heterogeneity emerges endogenously when property rights are spatially defined. Assume growers are identical in every way prior to insect invasion. An insect is introduced to one grove first, so following invasion the patches are no longer identical. Assuming the introduction of insects is exogenous, which patch is the weaker link is determined exogenously, but the degree of weakness of the link is endogenous. Indeed, if either patch were invaded first, then  $k_i(t) < k_j(t)$ , for  $t > 0$ , where  $t = 0$  is the time of invasion into the first patch. This introduces heterogeneity, and the difference in the growers’ values of  $k$  may be increased by endogenously determined spraying strategies, including payments to spray sooner from others.

The individual grower’s optimal spraying strategy tolerates fewer insects as the value of the capital at risk increases. Insects depreciate capital. Under autarky, after a period of time the grower first invaded must find himself with the most degraded and least valuable capital. As the grower’s capital degrades, he tolerates more insects because there is less value at risk, all else equal. Other growers, with more value at risk, prefer that the invaded grower behaved as if the invaded grower held capital of greater value. But, the grower with the least to lose emits the most insects. Because spraying has properties of a strategic complement, when the grower that is invaded first tolerates and emits more insects, this provides incentives for other growers to tolerate more insects. In this sense the problem is weaker link (Burnett 2006; Cornes 1993). The degree of heterogeneity that leads to the weaker link problem is partially endogenous and connected to strategic interactions.

### 3.5 Invasive species taxes

Economic solutions to environmental problems often focus on a Coasian system of property rights and exchanges or a Pigouvian system of taxes (Stavins 2011). The previous analysis suggests the possibility of a Coasian system of exchange. An alternative is a Pigouvian tax,  $\omega$ , per insect pest. The logic of the tax is that it increases the cost to the grower of carry insect pests and provides an incentive to spray at lower ACP levels, shifting the stopping

<sup>20</sup>Such an equilibrium is almost certainly unstable when perturbed with heterogeneous local information.



boundary downward to a socially desirable level. If insect dispersal is proportional to population levels, then the tax seems targeted at the amount of biological pollution. However, if managers do not remove citrus in response to the tax, then they cannot separate productive capital from insects.<sup>21</sup> The additional cost may reduce the profitability of capital providing an incentive to shift the stopping boundary upward.

**Proposition 2**—A Pigouvian tax on the level of invasive species carried or allowed to disperse can potentially provide a perverse incentive for control of the invader, if the tax undermines existing incentives generated by property.

Alter the instantaneous net payoff function to  $f(k(t), \omega x(t))$ , and modify Eq (5) to

$$V(k, x) = \int_t^{\tau^*(k, x; \omega)} f(k(s), \omega x(s)) e^{-\rho(s-t)} ds + e^{-\rho\tau^*(k, x; \omega)} (V(k(\tau^*(\cdot)), x(\tau^*(\cdot))) - c) \quad (15)$$

s.t. Eq (10) and Eq (12). Substitute in  $\tau^* = \tau^*(k, x; \omega)$  as the optimal spraying time as a function of the state variables and the per-insect tax (all other parameters have been suppressed). Apply the dynamic envelop theorem (Caputo 2005) and differentiate (15) with respect to  $\omega$ , with an application of Leibniz rule to the first RHS term in (15), recalling that  $\tau^*$  is chosen optimally so all optimality conditions must hold.

$$\frac{\partial V(k, x)}{\partial \omega} = \int_t^{\tau^*} f_\omega(k(s), \omega x(s)) e^{-\rho(s-t)} ds + \tau_\omega^* e^{-\rho\tau^*} (f(k(\tau^*), \omega x(\tau^*)) + V_k k_{\tau^*} + V_x x_{\tau^*} - \rho V(k(\tau^*), x(\tau^*))) - \rho \tau_\omega^* c e^{-\rho\tau^*} \quad (16)$$

The first RHS term is negative because  $f_\omega < 0$ ; this is the direct effect of the tax, which lowers profitability and is an income effect. The tax makes production more costly, reducing the value of the asset and providing an incentive to tolerate more insects. This occurs because growers cannot instantly increase citrus production. The second term is the optimized current value Hamiltonian minus the current value value function multiplied by the discounted marginal effect of  $\omega$  on the stopping time. Since the stopping time is chosen optimally, the term in the parenthesis, which is Eq. (6) set as a strict equality, vanishes (an envelope result). This condition must hold while waiting to spray. The third RHS term is the behavioral incentive, a substitution effect. Conditional on holding the asset value constant, the third term is positive. This creates an incentive for growers to spray sooner because it implies  $\tau_\omega^* < 0$ .

The marginal effect of the tax on the value of the asset,  $V(k, x)$  is ambiguous. If the income effect from the first RHS term dominates, then the overall effect of the tax on the asset value is negative, and there is a contradiction associated with the assertion  $\tau_\omega^* < 0$ . Therefore, the income effect of the Pigouvian tax can potentially “compete” with property incentives, nullifying the behavioral effect of the tax and leading to a greater tolerance of insects.

<sup>21</sup> Given the very high levels of ACPs per citrus tree reported in the literature, marginal reductions in citrus stock are likely to have little effect on the ACP stock. Therefore, marginal reductions in citrus stock in response to a tax are highly unlikely.

The tax potentially erodes the value of the asset being protected by spraying, dominates the behavioral incentive, and erodes the incentives provided by the future use of the property. Eq (16) implicitly provides an upper bound on the size of the income effect associated with a Pigouvian tax; Eq (16) must remain positive for the tax to have the desired behavioral effect.

It is a well-known normative result that in order for Pigouvian taxes to provide a first-best outcome the revenue from the tax must be returned to offset income effects from the tax (Sandmo 1975). This is seldom explicitly considered in natural resource economics, and the revenue recycling component of Pigouvian taxes for intertemporal externalities is often not mentioned. Indeed, Proposition 2 is developed without a revenue recycling mechanism. If the revenue were recycled in a way to exactly offset the income effects, then the first term in Eq (16) vanishes, and the tax is welfare enhancing. However, if the taxing authority cannot efficiently recycle the tax, insufficient revenue recycling could have qualitatively perverse *behavioral* effects in addition to generating welfare losses because the value of the productive asset being protected strongly influences the grower's abatement response. This result provides a reason to be cautious with invasive species taxes.

If the tax revenue is not perfectly recycled, then taxation could induce less spraying. In our model abandonment of production does not necessarily reduce emissions. Unlike other emission problems, the insect emissions are not a by-product of the active production process; rather insect "emissions" result from the existence of citrus capital, regardless of whether or not citrus capital is actively used to produce harvestable fruit. The USDA considers abandoned groves a problem in Florida and devotes resources to identifying and removing them (see footnote 10). The opportunity use of the land matters.<sup>22</sup> In some cases land may be repurposed quickly, while in others it may take time to repurpose land. During any delay a grove that continues to exist, but is not part of active production still emits ACPs. In canonical pollution problems, closing the producer is sufficient to stop the stream of pollution. It is immaterial whether the plant is repurposed, torn down or left vacant; emissions stop. In the case of biological pest pollution the underlying capital, which doubles as pest habitat, must be liquidated. This adds an additional, potentially non-trivial, dimension to designing incentive based policies that merits further consideration. O'Connell et al. (2009) suggest that removing citrus trees costs about \$1,025/acre, which makes the net present value of citrus reinvestment negative. For scale, the cost of citrus removal is approximately four times the annual rental value and 15% of the expected land sale value of agricultural land in the affected area of California (USDA NASS 2012). Furthermore, the act of removing trees, without spraying first, can cause ACPs to disperse out into neighboring areas (Rogers et al. 2011).

Taxing insects does not address these complications. These considerations have seldom been raised in the literature on Pigouvian taxes on pollution, but are particularly relevant considerations for invasive insect pests that may be able to spread relatively quickly. The real world importance of these considerations is an empirical question.

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<sup>22</sup>Antidotal evidence from Florida suggests livestock grazing under abandoned citrus trees is one potential alternative land use.

Richards et al. (2010) argue that a quota system rather than taxes may better complete the market when there is uncertainty on both the costs and benefits of abatement. Such a quota system would require monitoring. However, a quota could be seen as disclosing the upper bound on a neighbors stopping boundary. Such a quota system could pave the way for a spraying exchange market where transfers from one grower could incentivize other growers to spray earlier. The advantage of a market system is that marginal damages would be revealed in addition to marginal costs and transfers could be spatially explicit.

The efficient Coasian exchanges, Pigovian taxes, or quota system that internalized the externality depends on the marginal damages. The way that space enters as a risk factor and generates private expected costs to others matters. Incentives must be spatially explicit, as in other spatially explicit pollution problems (Goetz and Zilberman 2000; Muller and Mendelsohn 2009). ACP dispersal generates different damages depending emigration location. In the case of ACPs in agricultural landscapes most of the polluted resource is private citrus groves. The number of groves directly affected by self-dispersing or windblown insects may be quite small, making a Coasian solution of Pareto improving trades practical, particularly if human-mediated assisted dispersal can be addressed. Conversely, the relatively small number of groves may make any potential market thin and lead to trade coordination externalities and unrealized trading opportunities (Diamond 1982). Such trade coordination externalities may be particularly important for spatial externalities, particularly when strategic complementarities exist. Nevertheless, abatement only must happen once, while transferring pollution or allowing insects to disperse can happen many times, therefore the invention costs of rewarding spraying are likely lower than taxing insect emitters (Bird 1987). Furthermore, Hansen (2002) points out that taxes on jointly supplied and shiftable polluting stocks are likely to be infeasible. He argues that ideally a system of Coasian exchanges would emerge or the role of policy in such a situation should be to induce a market by compensating acceptors of the polluting stock.

If growers face uncertainty in the insect dispersal process, making the marginal benefits of payments to spray sooner uncertain or increasing transaction costs, then a true market of exchanges may increase prevention risk sensu Finnoff et al. (2007). There may also be uncertainty in optimal payment or cost of reducing dispersal probability. Finally, citrus is used as an ornamental in many public spaces or can become “ferial” and such public citrus may provide refugia for pests. The marginal benefits from preserving the citrus stock to noncommercial citrus may be significantly lower than to commercial owners (Ceddia et al. 2009).

#### 4. Discussion

The damages from invasion may be largely private, and the outmigration of pests from any one location may only directly exact costs on a small number of other locations. Furthermore, because pests exist in space they cause depletable externalities. Increasingly, researchers focus on the spatially explicit costs of invasion (Holmes et al. 2010), but seldom have researchers considered how the incentive properties of these costs lead to feedbacks on spread. An important question is if it is possible and optimal for land managers to further transfer the externality or accept and abate it (Bird 1987; Geaun 1993; Shaw and Shaw

1991). When land managers can exclude pest introduction, this represents a transfer of the externality (Warziniack et al. 2011). Such exclusion may be possible if human mediated dispersal is the only dispersal mechanism. But, once the invader takes hold any attempt to transfer the externality to others may simultaneously transfer pest to one's self in the future. This provides an incentive to start abatement. Controlling insects on one's property appears to be a strategic complement to neighbors controlling the pests on their properties. Owners of high value properties have stronger incentives to control pests, and risk from others reduces the value of private property reducing control incentives. This results in three policy considerations.

First, there is a connection between complementary strategic behavior and weaker link problems. Which grower is the weaker link depends on invasion history, which is partially endogenous to all growers' choices. It is in the best interest of other growers to cooperate with the weaker link and enhance the weaker link grower's value and private control incentives.

Second, private growers may prefer a Coasian system of transfers, particularly in the case of a few growers with good information. It is important to account for the incentives generated by private property to address spatial externalities. Pigouvian taxes have a greater risk of creating perverse incentives. Typically, it is assumed that a Pigouvian tax always yields qualitatively socially desirable behaviors, but may have perverse welfare effects if revenue is not recycled. We provide an example when a Pigouvian tax can potentially lead to perverse qualitative behavior, and revenue recycling is important to direct behavior in the socially desirable direction. Furthermore, the transferable nature of the externality suggests that compensating ACP accepters (and destroyers) would administratively less burdensome than taxing ACP providers (Bird 1987; Geaun 1993).

In a Coasian system of exchange, one may expect that a large number of participants could lead to free-riding and few exchanges would take place. But free-riding is unlikely when activities are strategic complements. More likely is that a small number of participants could lead to thin markets. Neighbor spatial relations and the role of space as a risk factor suggest that in many cases one individual's private marginal benefits from a neighbor's abatement may be sufficiently high to induce a payment. Moreover, citrus producers are also the ones who incur the bulk of the damages from insects so appropriate trading ratios (sensu Muller and Mendelsohn 2009) have the potential to emerge endogenously and update quickly. An additional concern is developing detection schemes and incentivizing accurate reporting (see Gramig et al. 2009 for a similar discussion in the context of livestock and disease). In a well-mixed landscape with many growers, reliable third-party detection may be necessary for developing a market for private spraying transfers. However, in a landscape with fewer edges between growers a "whistle-blower" scheme may be effective. Government or trade associations could play an important role in developing detection regimes. Finally, Hansen's (2002) strategy for inducing market exchanges could be employed.

Third, there is a need to address the liquidation of capital. Citrus capital is non-malleable, and disposal costs are non-trivial, particularly for infested groves. To our knowledge this is an issue that has not been previously discussed. It is often assumed that shutting production

ends the flow of pollution or that polluting capital is rapidly repurposed to a clean use. Such an assumption depends on perfect land markets, but this condition is unlikely to hold all the time in real economies. For invader producing landscapes this may not be the case, particularly in times of macroeconomic contraction such as 2008–2011, which is when ACPs invaded California. Most incentive based schemes do not directly address this issue.

Many invaders exist on private property, control is implemented by private landowners, and damages are largely incurred by private landowners who also have the potential to emit insects. Accounting for the role of property based incentives in the study of invasive species is important. Accounting for these private incentives generally implies that the biological potential for invaders to spread may be much greater than believed in the absence of endogenous behavioral responses and the scope for welfare enhancing policy interventions may be small (Fenichel 2013; Fenichel et al. 2011; Francis 1997). In the classic example of the cattle and the corn field (Coase 1960), the cattle are an invasive pest in the corn field, and without transactions costs the socially optimal resolution involves a system of payments. This suggests that it may also be feasible that infested growers compensate clean neighbors, but echoing Bird (1987) the dynamic nature of the problem makes this unsustainable. More likely, clean growers will wish to help infected growers control their pests. Our analysis of the incentives generated by property rights for controlling invasive species begs the question why don't control exchanges exist? We believe there is scope for government intervention to lower transaction costs and facilitate information exchange.

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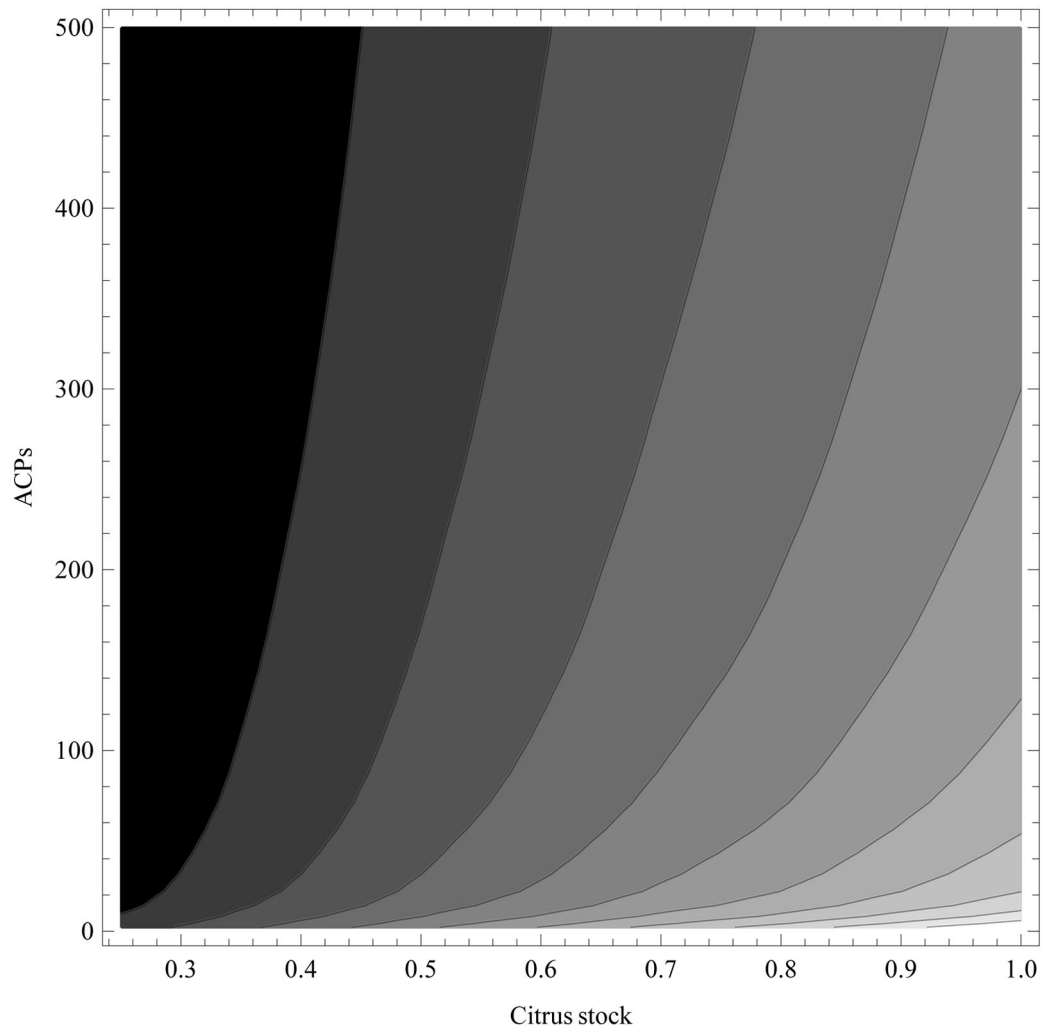


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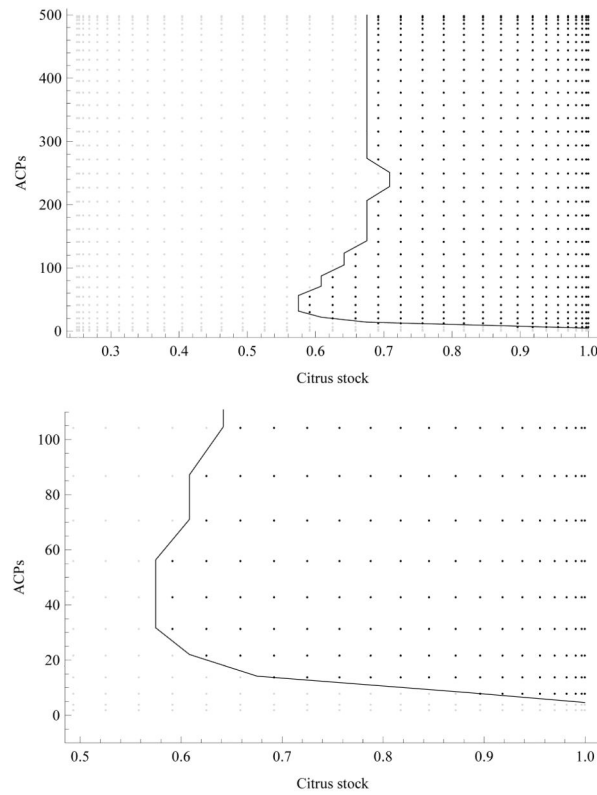
## Appendix

The choice of  $\beta$  is dependent on the extent to which HLB is present, which can be highly variable even within infected regions (Gottwald 2010). Our choice of  $\beta$  reflects a limited amount of HLB (Halbert and Manjunath 2004) and is within the range implied by Chiyaka et al. (2012). The net growth rate of ACP is highly variable and dependent on environmental conditions. Our choice falls within the range from the literature (Lui and Tsai 2000; Tsai and Liu 2000). The rate is lower than the average growth rate used by Chiyaka et al. (2012), but their growth model enables the net growth rate to change seasonally. This is why their model enables a longer persistence of citrus trees. Our growth rate is also reduced relative to the estimate provided by Richards et al. (in press), but still seems to give realistic results. The carrying capacity conversion coefficient,  $b$ , was chosen to be realistic but conservative by envisioning 10,000 ACP per tree as a maximal density, which is substantially lower than values reported in the literature, and a square grove with approximately 31 trees on a side.

The profitability parameter  $q$  was chosen so that growers were not too profitable, but that in the absence of ACP and HLB operations are a rational enterprise. Data from the University of California extension office suggests that citrus operations are at best marginally profitable (O'Connell et al. 2009). Spraying costs are often computed on a per acre bases and can be highly variable (Aubert 1987; Catling 1970; Cocco 2008). Therefore, our choice of  $c$  is chosen to match in a realistic way with the choice of  $q$ , though our parameter is likely on the low side of costs. The technical spraying parameter  $\alpha$  comes from (Setamou et al. 2010).

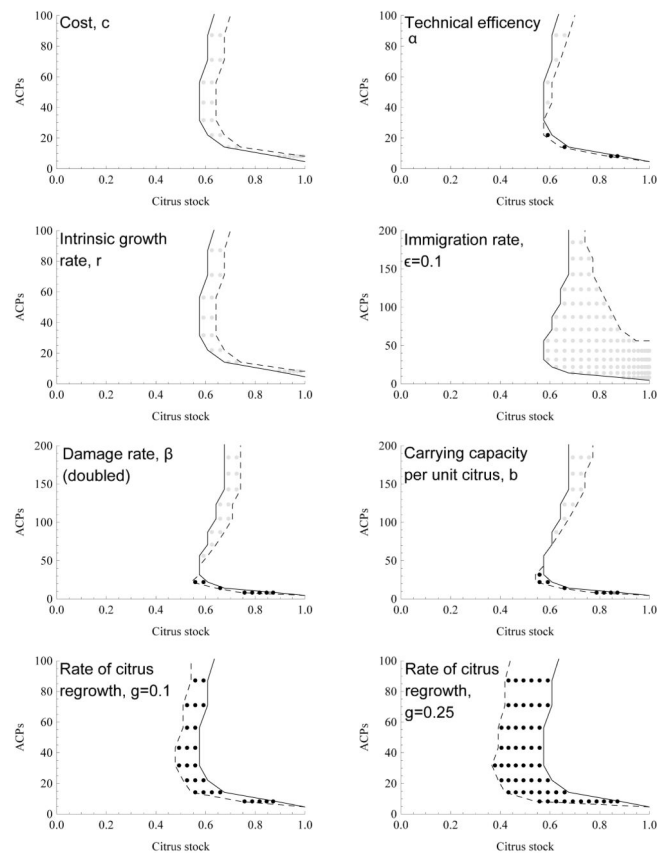


**Figure 1.**  
The optimized value function in  $k$ - $x$  space. Lighter shades indicate high values.



**Figure 2.**

Collocation nodes are shown as dots, with black dots populating the spraying region and gray dots in the continuation region. The lower panel enlarges the region relevant for inferring the stopping or spraying boundary during the invasion. The solid curve linearly interpolates the boundary between the waiting and spraying region.



**Figure 3.**

Sensitivity analysis to parameter changes. The parameter changed is label in the upper left of each panel. All parameters were increased by 10% except  $\epsilon$ , which was simulated at a value of 0.1,  $\beta$  which was doubled because a 10% change did not produce noticeable shifts at the density of nodes used, and,  $g$  which was simulated at the values 10% and 25% annual regrowth. The solid and dashed curves show a linear interpolation of the boundary between the continuation and spraying region for the base case and the case associated with the perturbed parameter respectively. Black dots indicate collocation nodes that were part of the spraying region under the alternative specification that were not part of the spraying region in the base case, i.e., expansions of the spraying region. Gray dots indicate collocation nodes that were part of the spraying region in the base specification, but are not in the alternative specification, i.e., contractions of the spraying region. Collocation nodes that did not change assignment to a region are not shown.

**Table 1**

Parameters, their descriptions, and the value used in the base numerical simulation

Parameter	Description	Value
$k$	Citrus stock	Variable
$x$	ACP stock	Variable
$\beta$	The feeding and damage rate of ACP on citrus	$1.0 \times 10^{-7}$
$r$	ACP growth rate	$1.43 \times 10^{-2}$
$\varepsilon$	Immigration rate of ACP	0
$a$	Technical spraying efficiency	0.1
$\rho^*$	Discount rate	$1.37 \times 10^{-4}$
$q$	The net revenue from citrus per day	0.5
$c$	Cost of spraying	50
$b$	Maximum number of ACPs that a citrus grove can support	$1.0 \times 10^{-7}$
$g$	Regeneration rate of citrus	0

\* the discount rate used is a 5% annual discount rate where the time step of the model is days.