Spread Rate Estimation and the Role of Spatial Configuration and Human Behavior

by

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ABSTRACT

The spread of invasive species may be greatly affected by human responses to prior species spread, but models and estimation methods seldom explicitly consider human responses. I investigate the effects of management responses on estimates of invasive species spread rates. To do this, I create an agent-based simulation model of an insect invasion across a county-level citrus landscape. My model provides an approximation of a complex spatial environment while allowing the "truth" to be known.

The modeled environment consists of citrus orchards with insect pests dispersing among them. Insects move across the simulation environment infesting orchards, while orchard managers respond by administering insecticide according to analyst-selected behavior profiles and management responses may depend on prior invasion states. Dispersal data is generated in each simulation and used to calculate spread rate via a set of estimators selected for their predominance in the empirical literature. Spread rate is a mechanistic, emergent phenomenon measured at the population level caused by a suite of latent biological, environmental, and anthropogenic. I test the effectiveness of orchard behavior profiles on invasion suppression and evaluate the robustness of the estimators given orchard responses.

I find that allowing growers to use future expectations of spread in management decisions leads to reduced spread rates. Acting in a preventative manner by applying insecticide before insects are actually present, orchards are able to lower spread rates more than by reactive behavior alone.

Spread rates are highly sensitive to spatial configuration. Spatial configuration is hardly a random process, consisting of many latent factors often not accounted for in spread rate estimation. Not considering these factors may lead to an omitted variables bias and skew estimation results.

The ability of spread rate estimators to predict future spread varies considerably between estimators, and with spatial configuration, invader biological parameters, and orchard behavior profile. The model suggests that understanding the latent factors inherent to dispersal is important for selecting phenomenological models of spread and interpreting estimation results. This indicates a need for caution when evaluating spread. Although standard practice, current empirical estimators may both over- and under-estimate spread rate in the simulation.

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INTRODUCTION

Ecological systems are heavily impacted by human decisions, and the spread of invasive species is of particular concern (Finnoff 2005; Perrings 2005). Changes in trade patterns (Costello et al. 2007), macroeconomic indicators (Perrings et al. 2010), and models based on human use behavior have helped explain and predict the spread of invasive species over large scales (Bossenbroek et al. 2007; Sharov et al. 1997). However, responses to invasive pests, particularly agricultural pests, are often local or regional and localized behaviors may matter for invasive species spread. Knowledge of invader spread rate is important for formulating cost-effective plans to control spread. Yet, spread rate is an *ex poste* phenomenological description of a system, and observed spread rates are emergent properties that arise as the result of invader biology and invader habitat interactions. The role of human response, and its role in shaping invader habitat in spread, is seldom considered in estimates of the rate of spread of an invader despite the fact that anthropogenic movement is commonly cited as a major cause of novel species introduction (Bossenbroek et al. 2007; Finnoff et al. 2005; Keller et al. 2007; Kolar, Lodge 2002; Leung et al. 2006), and the recognition that human response to invasive species are important for the establishment and damages caused by the invaders (Finnoff 2005). The economics literature largely focuses on optimal management and choosing the management path that maximizes net benefits while achieving a management goal (Epanchin-Niell, Hastings 2010; Fenichel et al. 2010; Homans, Horie 2011; Horan, Fenichel 2007), as opposed to actual decentralized behavioral responses. Biological models focus on the population dynamics of an invader and its spread, such as evaluating spread rates after management initiatives (Mercader et al. 2011; Sharov 1998a). However, most models do not consider human behavior explicitly, instead modeling human behavior implicitly through uncommon long distance invader jumps termed "stratified dispersal" (Kot et al. 1996; Shigesada, Kawasaki 1997; Shigesada 1995).

Many invasive species, and particularly agricultural pests, spread across private property. These pests create damages to individual properties (Holmes et al. 2010) providing an incentive for landowners to control pests (Epanchin-Niell 2012; Homans, Horie 2011; Potapov et al. 2007; Sharov 1998a). Heterogeneity among property owners creates a heterogeneous landscape across which the invaders spread. Most common estimators of spread rate assume a homogeneous environment (Hastings et al. 2005; Liebhold 2008). If landscape heterogeneity were fully exogenous to the state of the system, then one could estimate (assuming enough data) spread rates conditional on the observable sources of landscape heterogeneity. However, a key source of heterogeneity is the way in which people respond to invasive species. For example, spraying pesticides in response to the arrival of an insect pest is determined in part by the timing of the arrival of the pest. This implies that some aspects of landscape heterogeneity are endogenous to the ecological spread of the invader and human responses. Due to numerical complexity (Murray 2001), few studies explicitly consider space, opting to model space implicitly (Kinezaki et al. 2003; Sanchirico, Wilen 1999; Shigesada et al. 1986) or analyze it with visual imaging techniques (BenDor et al. 2006; Mercader et al. 2011). In this study, I investigate the robustness of alternative spread rate estimators to defensive adaptive human behavioral response to invader spread in a complex spatial environment.

Studying the robustness of estimators in the field is challenging because the "truth" is unknown. Rather than relying on field data to learn about the robustness of estimates, I follow an approach inspired by "management strategy evaluation" (Bunnefeld et al. 2011; Dichmont et al. 2008; Sainsbury et al. 2000). I simulate the invasion process at a finer scale than common spread rate estimators operate by creating an agent-based model that simulates the spread of insects and the behavioral response of multiple land managers to the insect invasion. The agent-based model allows me to treat space explicitly and generates dispersal data conditional on human reactions to invasion, which are used for estimating spread rates.

I base my model on the spread of the Asian citrus psyllid (*Diaphorina citri*), which is invading Southern California. Since its introduction to Florida in 1998, the Asian citrus psyllid (ACP) has spread across the United States into Louisiana, Alabama, Texas, Arizona, and California (USDA-APHIS 2011). Alone ACP is a minor pest but, as the vector for citrus greening disease (CGD), it has the potential to devastate the California citrus industry (Halbert, Manjunath 2004). With no known cure, the only way to contain citrus greening disease is through suppression of the Asian citrus psyllid (Halbert, Manjunath 2004). Further, with the introduction of CGD in March 2012, effective methods for estimating and monitoring the spread of ACP are highly needed.

Current spread rate estimators do not consider human behavior in their estimation methods, relying on presence/absence data, species counts, or distance metrics (Hastings et al. 2005; Liebhold 2008). Traditionally, empirical methods are simple, often requiring strong assumptions regarding species dispersal patterns and environmental heterogeneity (Hastings et al. 2005; Liebhold 2008). These are applicable for some specific species (Andow et al. 1990; Lubina, Levin 1988; Okubo 1988) but are not applicable in most cases. Emerging models have come to include environmental and human-caused factors (Havel et al. 2002; Jacquemyn et al. 2005; Richards et al. 2012; Whitmire, Tobin 2006), optimized algorithms for approximating population range (Tobin et al. 2007), and advanced imaging techniques (BenDor et al. 2006; Mercader et al. 2011) in evaluating spread. Although pivotal in forming and evaluating policy, little research has been conducted comparing estimators (Tobin et al. 2007). By implementing a set of common estimators, I evaluate the robustness of spread estimators to human behavior and analyze the factors contributing to spread rate.

The main contribution of this thesis is twofold. First, I indicate the need to incorporate human behavior in management and spread analyses, and suggest caution when evaluating spread rates with current empirical estimators. I show that spread rates are sensitive to orchard spatial configuration and biological parameterization as well as preventative management, and find qualitative and quantitative different estimation rates between estimators. Second, I provide a model framework that can be tailored to other invasive species and expanded to include more complex human behavior.

MATERIALS AND METHODS

The model

I create an agent-based model that generates insect dispersal data conditional on human reactions in order to investigate the sensitivity and cross-estimator consistency of the spread rate estimates to the data generating mechanism, which in practice includes potentially unknown human behavioral responses to the invasive insects. The agent-based model provides the known data generating mechanism. Using generated data, I estimate spread rate using a set of common approaches, then conduct a treatment regression to assess the magnitude of treatment effect of the human behavioral responses and insect spread parameters.

I create an agent-based model simulating the county-level infestation of an insect pest across two orchard landscapes: Bakersfield, California and an alternative analyst-generated environment (Figure 1). It is likely that pre-existing conditions that may be positively or negatively correlated with the ability of insects to spread in part determines the spatial patterns observed in the Bakersfield area – the spatial arrangements in Bakersfield are non-random. To better understand the role of non-random patterning of human dominated landscapes I also generate an "alternative" environment that consists of orchards randomly distributed across the landscape. This alternative environment retains the same number of orchards and the same land use proportions as the Bakersfield environment. A detailed description of the environment derivation can be found in the ODD Protocol (Appendix A). Orchard growers monitor insect spread and respond according to a management strategy or "treatment." By taking an agent-based approach, I create a data generating laboratory in which I may conduct experiments. Agent-based models give me the ability to develop a stochastic model that incorporates human behavior within a complex, spatially explicit environment.

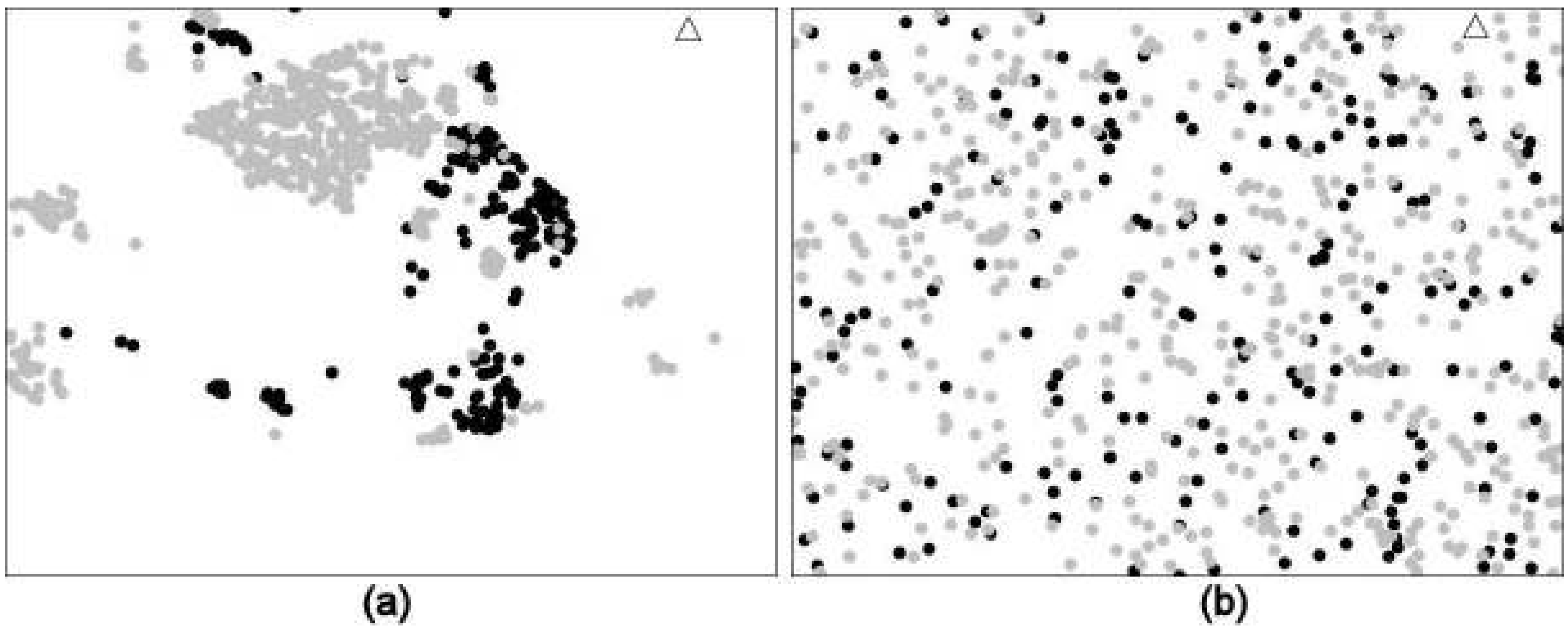

Figure 1. Orchard spatial configurations. (a) Bakersfield, CA and (b) an alternative, analyst-generated configuration. Black circles indicate the centroid of commercial citrus orchards; grey circles noncommercial orchards. Circle size does not represent orchard size. The invasion point of introduction or origin (triangle) is randomly generated around the border of the environment.

The agent-based model contains two types of computer agents: insects (ACP) and citrus growers. Grower agents are assumed to have exclusive property rights over a citrus orchard. I am concerned with the invasion process, and therefore simulate the first two growing seasons, measured as 730 time steps or "days," of the invasion. Over the same period, I simulate a stochastic, phenomenological model of individual insect dispersal that is aggregated to observed population-level dynamics (e.g. the biological baseline) and controls for human behavior. Each day insects disperse, feed, and reproduce, and then, based on the current local state, growers decide on a response: either spray for insects or delay control (Figure 2).

Figure 2. The sequence of events within a simulation time step. Events occur sequentially from left to right. Those along the solid line take place strictly within citrus orchards. ACP dispersal may occur both within and outside of citrus orchards.

Insect agents are parameterized to be Asian citrus psyllid (*Diaphorina citri*) (Table 1). ACP populations are assumed to grow geometrically and individual insects disperse with a bias towards citrus orchards. This is meant to approximate insect behavior in a manner more specific than a random-walk model (Catling 1973; Mead 1977; Wenninger et al. 2008) and allow for occasional long distance jumps caused by human transportation (Halbert, Manjunath 2004; Halbert 2010).

Table 1. Simulation parameter list.

Parameter	Value	Notes and References
Lifespan	28 (days)	Up to several months, depending on temperature and humidity (Halbert, Manjunath 2004; Husain, Nath 1927; Lui, Tsai 2000; Nava et al. 2007)
Developmental time (egg to adult)	16 (days)	15-47 days, depending on temperature (Halbert, Manjunath 2004; Husain, Nath 1927) with sexual maturity 2-3 days post eclosion (Wenninger, Hall 2007)
Intrinsic growth rate	0.2	Catling 1970; Lui, Tsai 2000; Tsai, Lui 2000; van den Berg et al. 1991
Starvation time	14 (days)	Average survival of adult *T. erytreae* range from a maximum of 55 hours (Catling 1972) to 3.65 days (van den Berg, Deacon 1988) to 17-50 days (Catling 1973)
Feeding efficiency	1.28×10^{-6}	Without citrus greening, Asian citrus psyllid is a minor pest (Halbert, Manjunath 2004; Knapp et al. 1998)
Insecticide efficiency	0.90	Qureshi, Stansly 2008; Srinivasan et al. 2008; Setamou et al. 2010
Insecticide duration	60 (days)	Up to several months, depending on insecticide and type of application (Aubert 1987; Qureshi, Stansly 2007; Setamou et al. 2008)

The distance each individual insect travels is independently drawn from a gamma distribution with a mean of the distance between the insect and the center of the nearest citrus orchard. The shape parameters of the gamma distribution are dependent on the distance a given insect is to the center of the nearest orchard and an analyst-defined coefficient of variation. Greater coefficients of variation increase the chances that insects will undershoot or overshoot an orchard. Psyllids likely remain within orchards if suitable hosts are present (Catling 1973). With the gamma distribution, most ACP engage in local dispersal within the orchard in which they are currently located, but the gamma distribution provides support for long distance dispersal (Walters et al. 2006).

Direction or angle of insect traveled is assumed to follow a beta distribution with support between zero and 180 degrees. The mean of the beta distribution is assumed to be 90 degrees. This establishes a "baseline" that is orthogonal to the expected angle of attack of the ACP on the center of the nearest orchard. ACPs locate hosts based on a mix of olfactory and visual cues (Wenninger et al. 2008) and are expected to orient towards a target orchard. The parameters of the beta are generated conditional on the centered mean with an analyst-specified coefficient of variation. Lower coefficients of variation imply that the insects hone more precisely to groves.

Growers respond to insect dispersal according to behavior profiles selected to reflect actual management techniques used in response to the Asian citrus psyllid (Table 2). Many options exist for managing the Asian citrus psyllid, varying in efficiency and duration of effect (Catling 1970; Cocco, Hoy 2008; Setamou et al. 2010). Spray technical efficiency (α) is modeled as reducing insect populations to a given percentage ($1-\alpha$) over the course of the treatment. Many insecticides are persistent in the environment but their effectiveness decays over time (USDA-NRCS 1998). The treatment effect of spraying is modeled to decay exponentially over time. At initial treatment, a spray exhibits its maximum effectiveness (α) then declines to a minimum (1-α) by the end of the duration. With ACP reproduction and immigration, this approach effectively reduces insect populations to (1-α) level at the end of the spray duration. I assume that application of insecticide ("spraying") occurs with 90% effectiveness and duration of two months (Setamou et al. 2010). For a detailed description of model initialization and execution, see the ODD Protocol (Appendix A).

Human behavior is modeled as the management response towards an insect pest. Colonies of invaders persist because of limited technical control measure efficiency or because populations are too small for detection (Shigesada, Kawasaki 1997). Citrus growers respond to insect levels based on a set of behavior profiles (Table 2, Figure 3). The baseline behavior is a detection threshold. Growers tolerate insects until the insect population reaches a detection threshold level, at which growers administer a control treatment (Martin et al. 2009). Threshold level can be thought of as the population level of insects required for grower managers to observe the presence of insects. Growers may also consider forecasted insect dispersal and state of invasion in surrounding orchards in addition to monitoring local insect population levels. Using a radial spread estimator, growers predict the future population range of the insect invader and spray if within the expected boundary of spread. Similarly, because infestation of a neighboring orchard increases the probability of being invaded, an orchard may administer a control if its nearest neighbor is infested. Alternatives to decision threshold profiles reflect current ACP management practices. Growers apply pesticides at temporal intervals, three times per year coinciding with new citrus flush (Hall et al. 2008; KAC 2012; Tsai et al. 2002) and monthly (KAC 2012).

The agent-based model was programmed in Mathematica 8.0 (Wolfram) and simulations were run in the Arizona State University Saguaro high performance

Table 2. Behavior profiles and simulation layout.

Orchard Layout	**Incentive structure**	**Incentive assignment**	**Spread parameterization**	**Management strategies (if ACP present)**	**Information Structure**
Bakersfield	heterogeneous	same/as is	high homing, low movement	threshold 150	own property
Alternate		same/random	high movement, low homing	threshold 250	own + neighbors
			high homing, high movement	interval (monthly)	own + predicted in next time step
			low homing, low movement	interval (x3/year)	

A heterogeneous incentive structure indicates that two type types of citrus orchards exist, differing in their management strategies – commercial and noncommercial (urban) citrus orchards. Noncommercial citrus is assumed to tolerate greater numbers of insects than commercial growers. Spatial configuration of orchard assigns behavior strategies to orchards as random (alternate) or pre-set (Bakersfield). Both spatial layouts possess the same proportional land use of orchards. Spread parameterization implies the ability of ACP to locate citrus orchards. Information structure indicates the amount of information available to commercial orchards in their management decisions, including a grower agents' own property, their own and their nearest neighbor, or their own and the predicted population range of ACP in the next time step, calculated from the radial spread estimator.

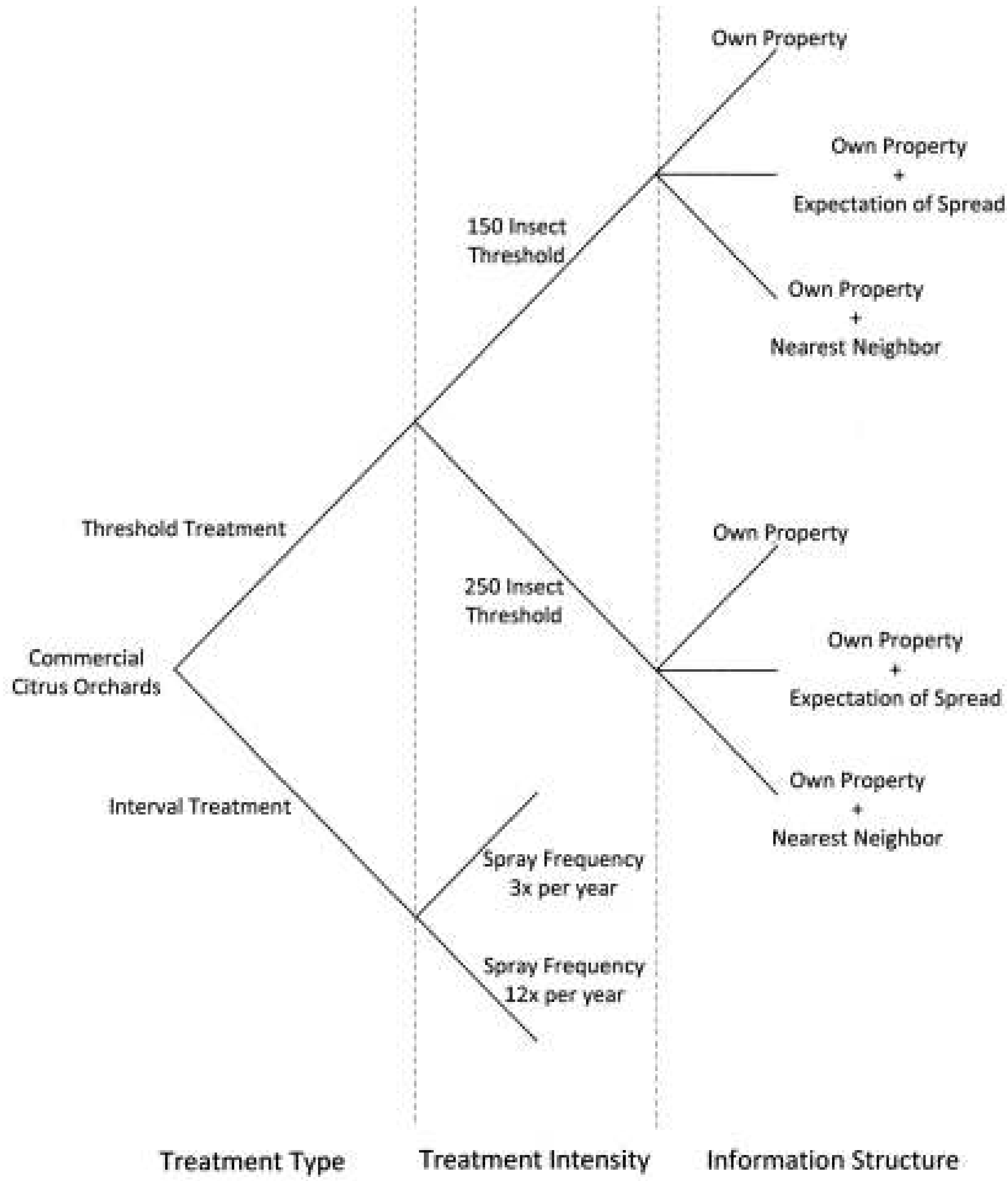

Figure 3. Commercial citrus orchard behavior profile tree. Commercial orchard growers possess one of several combinations behavior profiles, beginning with type of management, intensity of treatment, and level of information or "information structure." Growers that use an interval approach are restricted to their own property information level and act in a coordinated manner (e.g. all spray at the same time).

computing system. Simulations required a total time of approximately 120,000 CPU hours to complete.

Measuring spread at the population level

To evaluate the way the spread of the invasive species is measured, I compare seven spread rate estimators chosen for their predominance in the empirical literature (Tables 3 and 4). First, I adopt an approach utilized in studies of the gypsy moth (Liebhold et al. 1992; Sharov et al. 1997), maritime pine (Higgins, Richardson 1999), and emerald ash borer (Sargent et al. 2010). I conduct a linear regression of dispersal distances from the origin against time. The slope of the regression line is interpreted as the spread rate. The slope represents the expected change in distance from the origin per unit time. Many species experience linear increases in spread distances (Weinberger 2002), and Andow et al. (1990) argue that constant rates of species advance are good first approximations.

Second, I compare the maximum and minimum dispersal distances over the change in time between observations (Suarez et al. 2001). Maximum distance is defined as the distance of the furthest insect from the origin at a given moment in time. The origin is defined as the first point of observation. Minimum distance is the difference between the maximum distance and the closest observation from the previous measurement period. These techniques are known to over- and under-estimate spread rate, but can be used to construct an upper and lower bound of spread rate (Suarez et al. 2001). I also include a radial estimate of spread rate defined as the maximum dispersal distance divided by time (Shigesada, Kawasaki 1997).

Fourth, I adopt a simplified measure of spread common to the theoretical spread literature (Shigesada, Kawasaki 1997). Reaction diffusion and integro-difference models typically measure spread as a traveling periodic wave (Shigesada, Kawasaki 1997; Shigesada et al. 1986). Assuming a radial, constant spread, I estimate the speed of a travelling periodic wave front by calculating the diffusion coefficient, which is a modified squared average of dispersal distance (see Table 3). The spread of many species has been described by this approach, including the muskrat (Skellam 1951), sea otter (Lubina, Levin 1988), and house finch (Okubo 1988; Wikle 2003).

The fifth estimator follows the common practice of monitoring the change in species range over time, often by tracking the invasion front (Sharov 1998a; Shigesada, Kawasaki 1997). I calculate the circumference of the population front and its change over time assuming constant radial spread (Sharov 1998a). Sixth, I relax the radial assumption by estimating the change in the invasion front for each of the four cardinal directions (Kovalski 1998). These estimators provide a simplified approximation of the change in a species range while avoiding complex mapping techniques (BenDor et al. 2006; Mercader et al. 2011).

Seventh, I use an epidemiological approach to estimate spread. Similarities exist between the invasive species and epidemiology literature, paralleling invasion with infection (Mollison 1972): the presence or absence of disease within localities may be used an indicator of disease spread (Dhondt et al. 1998; Villafuerte et al. 1995). As spread rate increases, greater numbers of localities are infected. I measure prevalence of infestation by monitoring the proportion of infested orchards.

Because we believe that the distribution of estimates may be non-normal, I conduct a non-parametric bootstrap simulation to calculate the standard errors. Using spread estimates generated from the agent-based model, I bootstrap 1,000 replications for each treatment and estimator to find the standard errors and 95% confidence intervals.

Table 3. Dispersal distance estimators of spread.

Estimator	Calculation of Rate (R)	Units	Assumptions	Reference
Linear Regression	Slope of regression line	distance/time	Constant rate of spread	Liebhold et al. 1992; Sharov et al. 1997; Higgins, Richardson 1999; Sargent et al. 2010
Dispersal Interval Radial Spread	$R_{MAX,t} = \frac{D_{MAX}}{\Delta t}$ $R_{RAD} = \frac{D_{MAX}}{t}$ $R_{MIN,t} = \frac{D_{MIN}}{\Delta t}$	distance/time	Radial spread Constant rate of spread	Suarez et al. 2001
Diffusion Coefficient (D) Travelling Wave Speed (C)	$D = \frac{\left(\frac{\sum_{n=1}^{N}(distance\ of\ an\ individual\ from\ the\ origin)}{(total\ number\ of\ individuals)}\right)^2}{\pi * (time)}$ $C = R = 2\sqrt{\varepsilon\, D}$	distance/time	Radial spread Constant rate of diffusion Normality of data	Shigesada, Kawasaki 1997

D_{MAX} – maximum dispersal distance, D_{MIN} – minimum dispersal distance defined as the distance between the maximum distance of time *t* and the closest sighting time *t-1*, Δt – change in time between observations, ε - species reproductive rate (defined as 0.20).

Table 4. Population front estimators of spread.

Estimator	Calculation of Rate (R)	Units	Assumptions	Reference
Radial Change in Population Front	$L_t = 2\pi * D_{MAX}$ $R_t = \frac{L_t - L_{t-1}}{\Delta t}$	distance/time	Radial spread Constant rate of spread	Sharov, Liebhold 1998b; Shigesada, Kawasaki 1997
Average Change in Cardinal Directions	$R = \frac{(\sum \Delta\ in \max distance\ in\ cardinal\ directions)}{4 * (time)}$	distance/time	Simplified invasion front	Kovalski 1998
Prevalence of Infestation	$I = \frac{\%\ Infested\ Orchards}{t}$	# infested sites/time	Infestation defined as presence/absence	Vilafuerte et al. 1995; Dhondt et al. 1998

L_t – length of invasion front at time *t*, D_{MAX} – maximum dispersal distance, Δt – change in time between observations, I – rate of infested orchards (denoted I to indicate different type of measurement).

Analyzing the components of spread rate

Measured population level spread rate is an emergent property. Each individual insect has a behavior that attracts towards a citrus grove and each grower responds to the current or expected state of insects. Population level spread is a description of an emergent phenomenon that is affected by many finer scale modeling decisions. A full factorial design of the mechanisms that lead to an observed spread rate includes the effects of the human treatment response, orchard spatial structure (Bakersfield or alternative), and biological mobility-honing parameterization. I estimate the effect of the components of a treatment on each spread rate estimator.

I conduct a treatment regression to evaluate the magnitude of treatment effects on spread rate. Given the nature of simulation models, I am concerned with the sign and relative magnitude of the regression coefficients. Standard errors depend on the number of simulations run, and therefore hypothesis tests for statistical significance are inappropriate. My model specification takes the form:

$$y_e = X\beta + \varepsilon$$

where y_e is an 1 x 52,000 vector of spread rate estimates for a single type of estimator. X and β are n x m design matrix and m x 1 coefficient vector respectively. My data consists of 260,000 observations, 500 for each treatment and estimator (n = 52,000), and 8 variables denoting spatial structure, gamma coefficient of variation, beta coefficient of variation, commercial orchard management type, commercial and noncommercial orchard threshold levels, commercial orchard interval level, and the interaction between a commercial threshold policy and information structure. For each observation, I calculate seven estimates of spread rate ($y_{e,\,n}$). Analyses of spread rate estimates were conducted in Stata version 11.0 (StataCorp).

RESULTS

Summary Statistics

Spread estimates differ between linear regression, radial spread, and traveling periodic wave front approaches (Figures 4 and 5, Appendices B and C). In almost all cases, given a treatment, parameterization, and spatial structure, the 95% confidence interval of each estimator does not contain the means of the others. The traveling periodic wave front and radial estimates fall between the maximum and minimum spread. A linear regression method produces spread rates smaller than other estimation approaches, lower than the minimum bound, and occasionally less than zero.

Differences between estimators lie in their assumptions concerning the distribution of insect dispersal (Table 3). A constant radial spread rate implies that insects are uniformly distributed inside the population range up to the maximum distance from the origin, which is generally not the case. Due to inhospitable environments, inter- and intra-species specific effects, etc., species rarely spread at a constant rate in all directions from the origin (Hastings et al. 2005; Liebhold 2008). Thus, a radial estimator overestimates spread compared to approaches that consider a non-constant spread.

The diffusion coefficient accounts for the distribution of insects by incorporating the distances of all insects from the origin per estimation period – in taking a modified squared average of dispersal distances, fewer insects far away from the origin will have a smaller effect on spread rate than with the radial estimator. A traveling periodic wave speed accurately measures spread rate only when insect dispersal distance is a normally distributed and there is a constant rate of diffusion (Shigesada, Kawasaki 1997). (Many studies convert the x, y coordinate system to one dimension in order to model space implicitly.) Like in nature, there is no reason to believe that the ACP agents in my simulation adhere to the radial and constant diffusion assumptions in a hostile

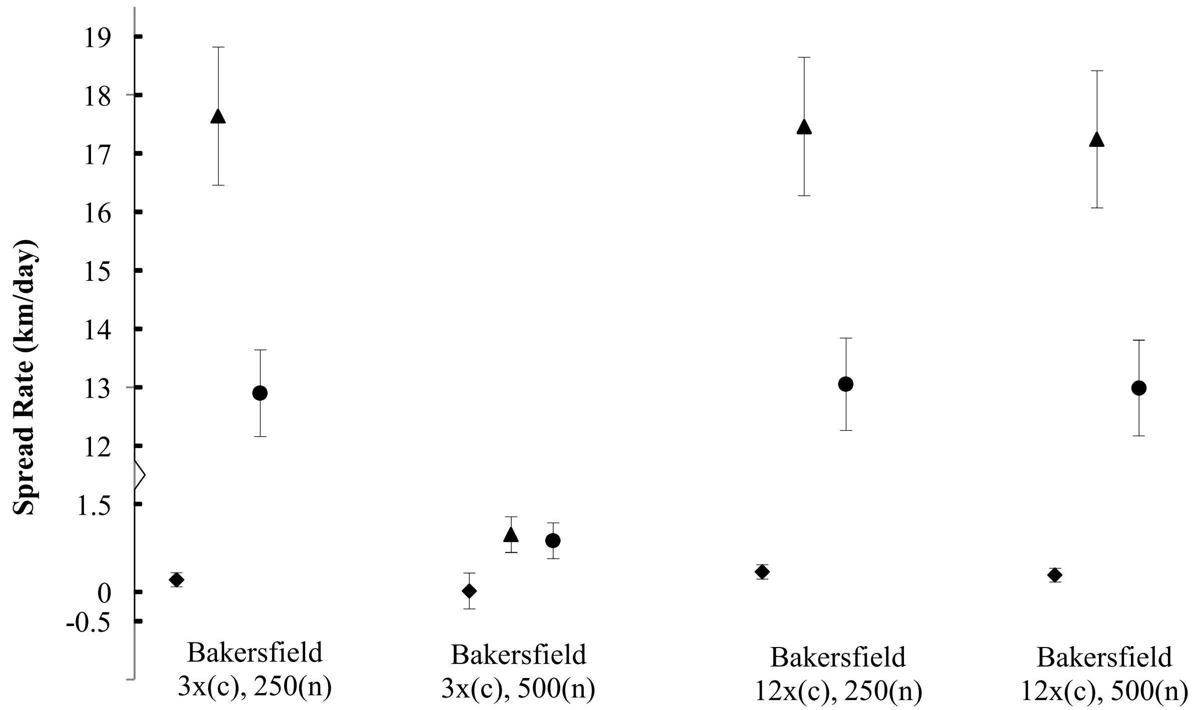

Figure 4. Average spread rate estimates under an interval treatment in the Bakersfield orchard configuration. Marker shape indicates spread estimator: linear regression (diamond), radial estimator (triangle), traveling periodic wave speed (circle). (c) and (n) describe commercial and noncommercial treatment strategies given as frequency per year (c) and the level of tolerance as the number of insects required before spraying (n). Vertical bars denote 95% confidence intervals. Marker location indicates the average spread rate. ACP agents are parameterized for high movement, low honing.

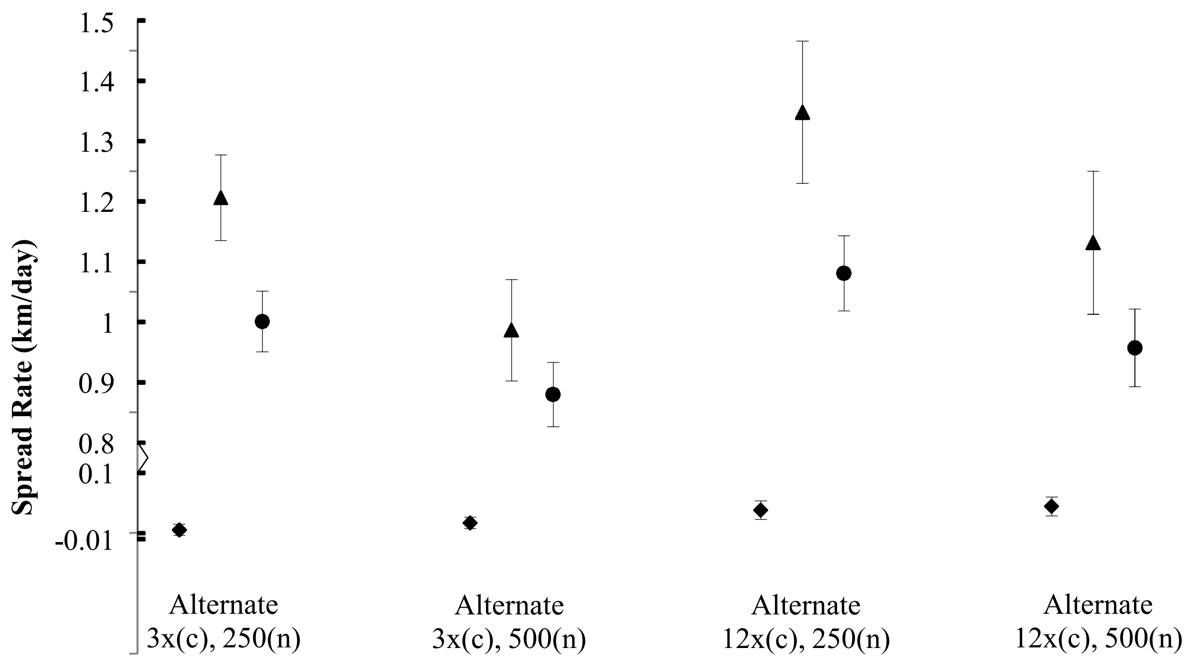

Figure 5. Average spread rate estimates under an interval treatment in the alternative orchard configuration. Marker shape indicates spread estimator: linear regression (diamond), radial estimator (triangle), traveling periodic wave speed (circle). (c) and (n) describe commercial and noncommercial treatment strategies given as frequency per year (c) and the level of tolerance as the number of insects required before spraying (n). Vertical bars denote 95% confidence intervals. Marker location indicates the average spread rate. ACP agents are parameterized for high movement, low honing.

environment. However, traveling periodic waves have been show to provide a good first approximation of observed spread rates (Andow et al. 1990; Grosholz 1996).

A linear regression estimator results in the lowest spread rates by weighting the distribution of insects over the course of the entire simulation. It also includes the possibility of negative spread rates. Negative spread rates occur if insects initially spread across the environment, but then recede backwards due to treatment. Alternately, long distance dispersal may cause small populations to form ahead of the primary population front, which increase spread (Homans, Horie 2011; Shigesada, Kawasaki 1997); eradication of outlier colonies will cause a decline in spread rate.

Alone without human assistance, ACP are thought to be able to travel up to 1.5 kilometers per day (Arakawa, Miyamoto 2007; Aubert, Hua 1990; van den Berg, Deacon 1988). For the Bakersfield spatial structure, only the minimum bound and linear regression approaches provide estimates of spread rate that fall within the range of the Asian citrus psyllid dispersal. The alternative layout yields spread rate estimates in the dispersal range of ACP for all but the maximum bound, suggesting that spatial structure plays an intrinsic role in determining spread rate and that approaches based on homogeneous environments can be misleading. For example, the radial spread estimator is an order of magnitude larger in the Bakersfield spatial configuration than the alternate (Figures 4 and 5). The large-scale spread of ACP has been attributed to human transport (Halbert, Manjunath 2004; Halbert 2010). Spread rates greater than expected ACP dispersal distance are likely due to infrequent long distance dispersal jumps, which violate constant spread assumptions and have been shown to increase spread rates in more complex models (Kot et al. 1996).

Approximating changes in population range under a radial population front estimator overestimates species expansion compared to measuring the average change in cardinal directions (Figures 6 and 7, Appendices B and C). The change in a radial front essentially evaluates the differences in the circumference of a circle. Population ranges are rarely perfectly circular, resulting in the radial population range estimator possessing higher changes in species range than an average change in cardinal directions. Further, the Bakersfield orchard structure possesses a less continuous orchard environment than the alternative. The Bakersfield layout contains stretches of uninhabitable environment interspersed between viable clusters of orchards. Once ACP reach the border of the types of environments, ACP must disperse across the uninhabitable environment to reach other orchards, limiting spread in that direction.

Spread rates are more sensitive to spatial configuration of orchards and insect mobility and honing parameterization than human response (Figures 8 and 9, Appendices B and C). Although there are differences between threshold and interval treatments, there are few noticeable trends in the spread rate. Low mobility and poor honing by ACP tend to produce low spread rates, while high mobility and honing lead to greater spread rates, especially when measured by linear regression and period wave speed estimators. Higher beta and gamma coefficients of variation increase the probability of an insect missing and overshooting a target orchard, potentially infesting other orchards and increasing spread, but also decrease the ability of ACP to locate orchards. In the case of low coefficients of variation, insects are able to effectively target orchards. Although infrequent, when long distance dispersal occurs ACP may effectively locate orchards, increasing the likelihood of infestation. Orchards tend to have lower numbers of spray events when coefficients of variation are low (Table 5, Appendices D and E). Insect populations are kept low by orchard management, indicating that insect agents generally remain within orchards – a high spread rate may be attributed to high honing ability after a long distance dispersal event.

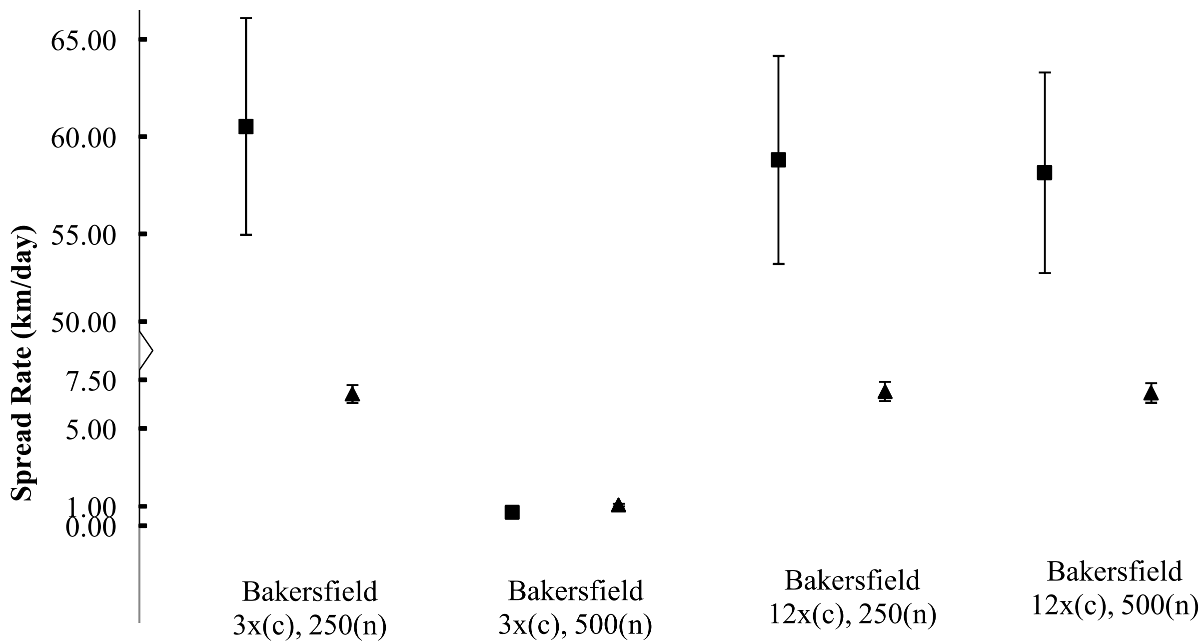

Figure 6. Radial change in population front and change in cardinal directions estimates under an interval treatment in the Bakersfield orchard configuration. Marker shape indicates spread estimator: radial change in population front (square) and average change in cardinal directions (triangle). (c) and (n) describe commercial and noncommercial treatment strategies given as frequency per year (c) and the level of tolerance as the number of insects required before spraying (n). Vertical bars denote 95% confidence intervals. Marker location indicates the average spread rate. ACP agents are parameterized for high movement, low honing.

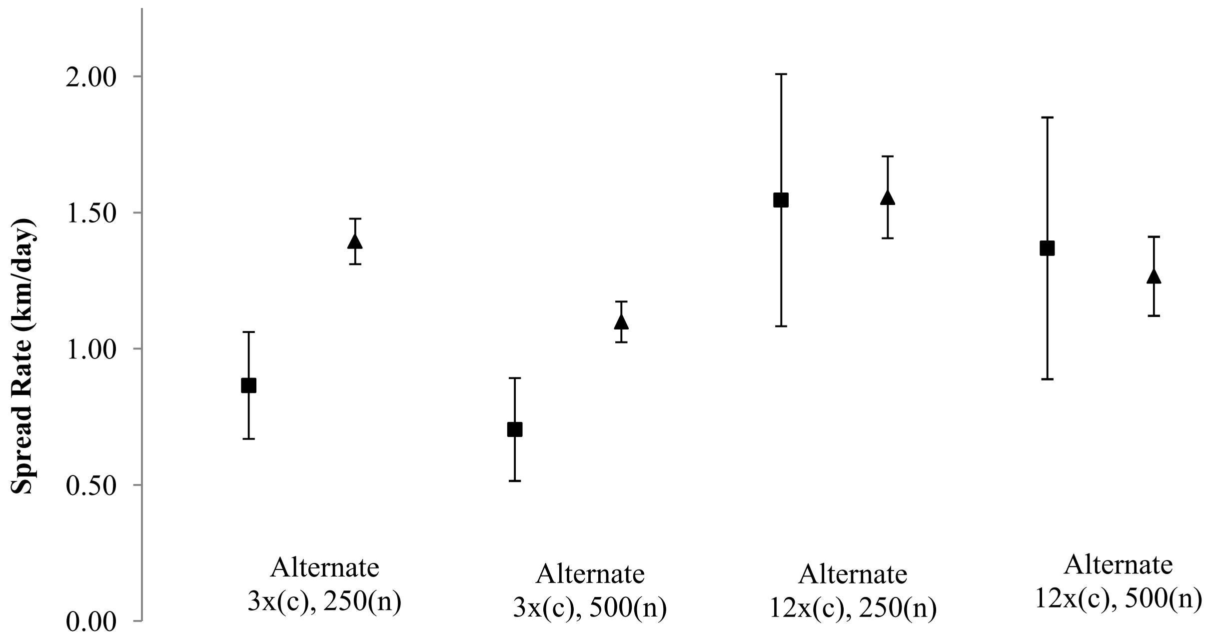

Figure 7. Radial change in population front and change in cardinal directions estimates under an interval treatment in the alternative orchard configuration. Marker shape indicates spread estimator: radial change in population front (square) and average change in cardinal directions (triangle). (c) and (n) describe commercial and noncommercial treatment strategies given as frequency per year (c) and the level of tolerance as the number of insects required before spraying (n). Vertical bars denote 95% confidence intervals. Marker location indicates the average spread rate. ACP agents are parameterized for high movement, low honing.

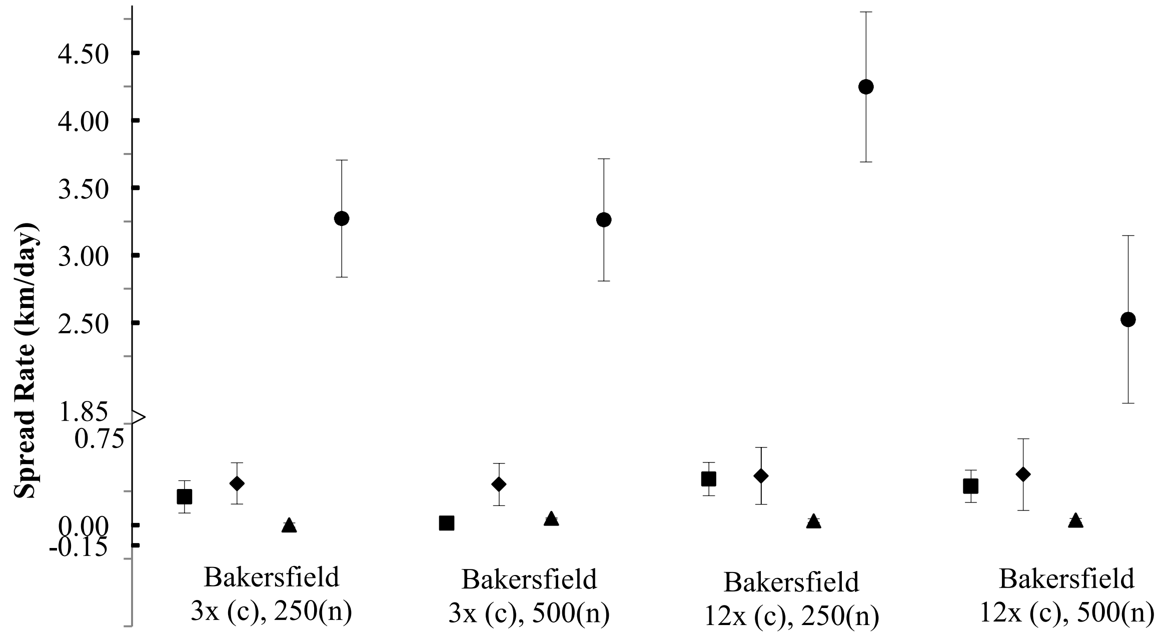

Figure 8. Linear regression spread rate estimates under an interval treatment in the Bakersfield orchard configuration. Marker shape indicates ACP biological parameterization: high mobility, low honing (square), low mobility, high honing (diamond), low mobility, low honing (triangle), high mobility, high honing (circle). (c) and (n) describe commercial and noncommercial treatment strategies given as frequency per year (c) and the level of tolerance as the number of insects required before spraying (n). Vertical bars denote 95% confidence intervals. Marker location indicates the average spread rate.

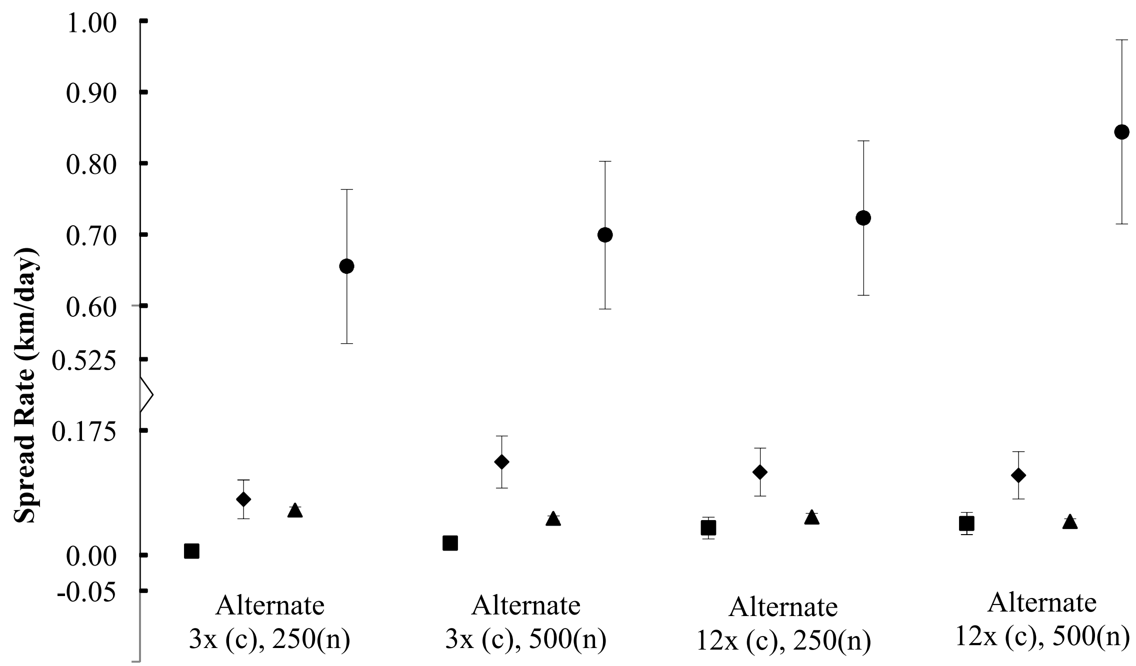

Figure 9. Linear regression spread rate estimates under an interval treatment in the alternative orchard configuration. Marker shape indicates ACP biological parameterization: high mobility, low honing (square), low mobility, high honing (diamond), low mobility, low honing (triangle), high mobility, high honing (circle). (c) and (n) describe commercial and noncommercial treatment strategies given as frequency per year (c) and the level of tolerance as the number of insects required before spraying (n). Vertical bars denote 95% confidence intervals. Marker location indicates the average spread rate.

Generally spread rates within the alternative environment are lower than the Bakersfield environment. In the alternative environment, the orchard layout is constructed such that commercial and noncommercial orchards are randomly generated within the landscape resulting in greater interspersion of groves across the landscape, as opposed to clustering in the Bakersfield scenario. Since the origin of introduction is randomly placed on the edge of the environment, ACP initially have less distance to travel resulting in a lower spread rate than the Bakersfield layout. Furthermore ACP must exhibit long distance dispersal to jump from cluster to cluster when orchards are clustered, which increases spread rate in my radial estimates (Shigesada, Kawasaki 1997). However, the clusters of orchards inherent in the Bakersfield configuration may present a more realistic scenario: ACP are initially introduced away from viable orchard habitats (e.g. a produce market) but find their way to local citrus orchards on their own or via human aid.

Including information of future spread in commercial grower management decisions tends to decrease the number of infested orchards for both commercial and noncommercial orchards, but increases the number of sprays per commercial orchard (Table 5, Appendices D and E). As commercial growers act in a preventative manner spraying before insects are present, they reduce insect spread but incur costs of extra management. Mobility and honing parameterization of ACP does not seem to affect the average number of infested orchards or spray counts (Appendices D and E). Although precision in mobility and honing increase spread, orchards do not experience increased infestation or management, suggesting that ACP remain localized around their nearest orchard and long distance jumps to other orchards are responsible for the high spread rate. In some sense this is problematic, because none of the estimates actually account for a jump stochastic process. Nevertheless, this is what appears to drive dispersal.

At initialization, insects are randomly generated on the border of the environment, and not within a citrus orchard. In the event that sufficient numbers of insects are not able to locate orchards and establish, spread estimates will reflect the initial spread and dispersal from the origin or at best the spread of the first few generations of insect invaders. Future models should generate ACP within an orchard along the border of the environment, guaranteeing initial insect establishment.

Analysis of spread rate components

Orchard spatial configuration and ACP biological parameters have the greatest effect on spread rate, possessing the greatest magnitudes and t-statistics of all regression coefficients (Tables 6 and 7). From my summary statistics, spread rates tend to be greater for the Bakersfield spatial structure and with lower coefficients of variation. I would expect the same qualitative results from my regression coefficients: increasing the coefficients of variation for ACP mobility and honing decreases spread rate, while spread rate is higher in the Bakersfield orchard layout than the alternative analyst-generated environment. This is the case for all estimators. Orchard spatial structure, which is not the result of random processes, plays a large role in determining spread rate. Similarly, insects that can effectively locate suitable habitat are able to spread faster than insects that do not.

For all estimations, the threshold treatment regressor is positive, indicating that the use of a threshold policy increases spread rate compared to an interval spraying approach (Tables 6 and 7). Although little research has directly compared the two approaches, it is generally accepted that coordinating insecticide administration with the citrus flush cycle is the most effective method for controlling ACP (Hall et al. 2008; Tsai et al. 2002). However, it is also possible that coordination in time of spraying controls

Table 5. Average counts of infested orchards and management in the Bakersfield orchard configuration.

		Commercial Orchards		Noncommercial Orchards	
Treatment	**Information Structure**	**# Infested Orchards**	**Sprays per Orchard**	**# Infested Orchards**	**Sprays per Orchard**
150(c), 250(n)	own property	4.182	0	6.756	0
150(c), 250(n)	expectations	2.282	0	9.436	9.148 E -5
150(c), 250(n)	nearest neighbor	3.184	0	5.992	1.663 E -5
150(c), 500(n)	own property	2.956	0	6.930	0
150(c), 500(n)	expectations	3.718	4.019 E -4	6.466	4.158 E -5
150(c), 500(n)	nearest neighbor	3.740	0	5.626	0
250(c), 500(n)	own property	2.826	0	8.054	8.316 E -6
250(c), 500(n)	expectations	2.768	4.299 E -4	6.634	1.223 E -4
250(c), 500(n)	nearest neighbor	3.212	0	5.462	8.316 E -6

(c) and (n) denote commercial and urban management strategies given as tolerance thresholds of ACP before spraying. Information structure includes only reacting to insect populations on their own property (own property), own property and an expectation of future spread as given by the radial spread estimator (expectations), and own property and the state of infestation on the nearest neighbor property (nearest neighbor). Units reported are averages per simulation. ACP agents are parameterized to have high movement and low honing. The reader should note that commercial and noncommercial orchards are independent of each other, tied only by insects dispersing between them – insects may only invade one type of orchard during a simulation, leading to unbalanced sprays counts between the types of orchards.

Table 6. Effects of treatment, environment, and parameterization on distance estimates of spread rate.

Coefficient	**Linear Regression**	**Radial Estimator**	**Travelling Periodic Wave Speed**
Spatial Configuration	0.328 (35.03)	4.924 (218.49)	4.887 (273.03)
ϒ-CoV (mobility)	-0.360 (-38.44)	-1.834 (-81.37)	-1.618 (-90.42)
β-Cov (honing)	-0.382 (-40.77)	-2.303 (-102.19)	-1.180 (-65.91)
Threshold Management	0.021 (1.22)	0.448 (11.03)	0.555 (17.20)
Commercial Threshold Level	-0.046 (-2.16)	0.078 (1.52)	0.060 (1.48)
Commercial Interval Level	-0.027 (-1.61)	-0.258 (-6.34)	-0.426 (-13.19)
Urban Threshold Level	-0.014 (-1.27)	-0.261 (-10.15)	-0.225 (-11.04)
Expectations | Low Commercial Threshold	-0.039 (-2.33)	-0.149 (-3.67)	-0.127 (-3.92)
Nearest Neighbor | Low Commercial Threshold	0.021 (1.26)	0.010 (0.24)	-0.072 (-2.24)
Expectations | High Commercial Threshold	0.088 (3.68)	-0.258 (-4.49)	-0.262 (-5.74)
Nearest Neighbor | High Commercial Threshold	0.015 (0.61)	-0.263 (-4.57)	-0.161 (-3.53)

Coefficient estimates are reported as magnitude (t-statistic).

Table 7. Effects of treatment, environment, and parameterization on population front estimates of spread.

Coefficient	**Average Radial Δ in Population Front**	**Average Δ in Cardinal Directions**
Spatial Configuration	17.998 (185.43)	1.770 (102.36)
ϒ-CoV (mobility)	-5.574 (-57.43)	-2.144 (-124.00)
β-Cov (honing)	-8.020 (-82.63)	-0.799 (-46.18)
Threshold Management	2.697 (15.41)	0.694 (22.24)
Commercial Threshold Level	0.107 (0.48)	-0.130 (-3.29)
Commercial Interval Level	-0.750 (-4.28)	-0.180 (-5.77)
Urban Threshold Level	-0.836 (-7.56)	-0.040 (-2.00)
Expectations | Low Commercial Threshold	-0.738 (-4.22)	-0.189 (-6.06)
Nearest Neighbor | Low Commercial Threshold	-0.088 (-0.50)	-0.148 (-4.74)
Expectations | High Commercial Threshold	-0.865 (-3.50)	-0.377 (-8.56)
Nearest Neighbor | High Commercial Threshold	-0.947 (-3.83)	-0.241 (-5.46)

Coefficient estimates are reported as magnitude (t-statistic).

insects.

Coefficients for commercial and noncommercial threshold yield estimates of the effect of increasing tolerance to insects in commercial (conditional on a threshold management policy) and noncommercial orchards. Similarly the coefficient for interval frequency implies the effect of decreasing the frequency of sprays. One hypothesis is that spread rates increase as orchards tolerate greater numbers of insects. However, coefficients are negative in all cases except for commercial thresholds with a radial spread estimator, traveling periodic wave front estimator, and radial change in population front (Tables 6 and 7). Magnitudes and t-statistics are lower for the commercial threshold, implying that commercial thresholds have a less significant effect on spread than a noncommercial threshold and commercial interval approach, supporting my result from the treatment threshold coefficient. In order to prevent deflated spread rates, I estimate spread only when insect populations are present in the model environment. If orchards are able to quickly eliminate an invading population, then spread rates will reflect the initial phase of invasion, which is known to possess high spread rates (Shigesada, Kawasaki 1997).

By including an interaction term between commercial threshold management and information structure I model the effect of supplying commercial growers with information of future of spread in their management decisions. Allowing growers to spray preventatively in response to expectations of future spread, in combination with present insect population levels, lowers spread rates compared to a threshold policy alone (Tables 6 and 7). Conditional on threshold level, spraying in response to infestation of a grower’s nearest neighbor and own property decreases spread rate in all but two estimations (Tables 6 and 7). Acting in a proactive manner, commercial growers spray before insect arrival, preventing infestation of one’s orchard and potentially creating a barrier to slow spread. A preventative management policy may provide a viable alternative if eradication or control approaches are not appropriate.

.DISCUSSION

Prevention: An effective policy for reducing species spread

Three types of management practices exist in the invasive species literature: prevention of invasion, eradication of a present invader, and control of invader populations (Horan et al. 2002). Economically a property manager would try to find the ideal or "optimal" choice that maximizes profits or minimizes costs. Although with preventative management one incurs costs with no invaders present, this may still be the optimal decision, particularly if the expected damages caused by the invader are severe (Finnoff, Shogren 2004; Horan et al. 2002). For instance, in the case of the zebra mussel (*Dreissena polymorpha*) invasion in North American, Leung *et al*. (2002) found significantly lower costs when preventative measures were undertaken to prevent spread from an infested lakeside power plant.

My results indicate that preventative measures reduce spread, albeit by increasing the number of sprays per orchard (Table 5, Appendices D and E). Introducing forecasts of future spread to a threshold management approach produces lower spread rates than with a threshold alone, for a given threshold. As growers respond to expectations of future spread, they lower the probability of invasion into their property. Further, if acting in a coordinating manner, growers may create a type of barrier zone containing the invasion, a technique well known for suppressing spread (Sharov 2004, 1998b).

The interval treatment is, in effect, a preventative management policy. Since commercial growers act in a coordinated manner not tied to level of infestation, they spray regardless of the presence of insects, and produce lower spread rates than a threshold management approach. However, more sophisticated threshold-based approaches than those explored here may be able to achieve comparable or reduced spread rates with fewer spraying events.

In order to better evaluate the performance of a preventative management policy, future work should include a cost-benefit analysis for treatment types. By recordings the productivity of orchards and the number of management sprays, we may calculate the net profits earned by each orchard as the difference between the benefits off added productivity and the costs of management. Evaluating the treatment that provides the maximum net profits provides a first approximation of the "optimal" strategy without solving an optimal control problem.

Prevention is likely a beneficial policy for California ACP management. Alone ACP are a minor pest (Halbert, Manjunath 2004), but with the introduction of citrus greening disease in March 2012, the potential damages of ACP have greatly increased. Once established, past history of ACP management indicates that eradication is not possible. Due to unique conditions of isolation and biological control, only Maritus and Reunion islands have been able to eliminate ACP and citrus greening disease (Halbert, Manjunath 2004; Yang et al. 2006).

Using Florida as an example, despite effective control of psyllid populations, ACP were able to spread quickly from its initial point of introduction in 1998 to every citrus producing county in the state (Halbert, Manjunath 2004). Preventative management may provide a method of slowing the spread if eradication or control is not possible.

Spatial configuration and invasive species spread

Spread is an individual based process, and spread rates are an ex post aggregation of these individual behaviors. Spread rate consists of a variety of latent species-specific and environmental variables, many of which are not accounted for in common spread estimators. Although some models include more complex biological factors (Hastings et al. 2005), few have focused on those inherent in the spatial configuration of hospitable environment for invasion.

In addition to the biological characteristics of an invader, the environmental layout plays a significant role in the success and spread of an invading organism (Hastings et al. 2005). For instance, Kinezaki (2010; 2003) linked lower spread rates to fragmented and patchy spatial configurations, in which hospitable habitats are broken up by uninhabitable areas. My results indicate a strong effect of spatial configuration on estimated spread rates. The Bakersfield orchard layout possesses greater spread rates than the alternative, randomly-generated, orchard layout. A clustered layout is the true case for California's ACP invasion and more likely to be the case empirically in general because the spatial configuration of orchard habitat suitable for invasion is not generated randomly. In the case of agriculture, commercial growers choose farm sites based on infrastructure, land prices, and suite of other factors not spatially uniform on the landscape. Even urban growers (e.g. hobbyist gardeners), which likely play an important role in the spread of industrial pests (Ceddia et al. 2008), may exhibit clustering around residential neighborhoods (particularly in the case of homeowners associations that may prefer certain landscaping types). Not accounting for environmental factors may lead to an omitted variables bias in spread rate estimation.

Estimation methods are beginning to include environmental factors in spread rate estimation. In predicting the probability of invasion in Missouri lakes, Havel *et al.* includes ecological variables inherent to aquatic environments (e.g. temperature, depth, nutrient levels) as well as zooplankton biology in their analysis (2002). Richards *et al*. (2012) factors in both biological and anthropogenic environmental variables in analyzing California Asian citrus spread. Since ACP may rely on multiple pathways for dispersal, Richards et al. incorporate wind direction, temperature, distance to highways, and home foreclosure in a stratified diffusion model. They find that each has a significant effect on the rate of spread, and predict lower spread rates than my estimation. Although we use different types of models, a large component of the differences in our approaches is the inclusion of environmental data.

Similarly, policy should consider the spatial layout of the landscape. Providing incentive to coordinate spraying between growers may aid in the creation of barrier zones of uninhabitable environment (due to management), containing or slowing the spread of the invader. Due to the clustered nature of the landscape, it is possible to coordinate management to "push" the invader into an area of uninhabitable environment (Epanchin-Niell 2012). But because of long distance dispersal, ACP have the potential to bypass management zones - multiple levels of spatial coordination may be required for effective containment of the invader.

Future research should account for spatial configuration in model analysis. In addition to data-utilizing models, agent-based models provide a unique opportunity in which within the virtual environment analysts may control both biological and anthropogenic factors involved in the model.

Spread rates: Inconsistency among spread rate estimators

Although important in evaluating the success of policy, few studies explicitly compare spread rate estimators (Tobin et al. 2007) but those that do often find different estimates. In a study of historical gypsy moth spread, Liebhold *et al.* (1992) utilized a linear regression and simple diffusion model to estimate distinct periods of dispersal. Their dispersal model produced much lower spread rates than a linear regression approach. Tobin *et al.* (2007) compare a linear regression approach to an optimized system of monitoring the displacement of gypsy moth population boundaries over time.

They find that the boundary displacement method predicts past spread more accurately than the linear regression approach, presumably due the displacement method's ability to better account for variability over space and time.

Similarly, I find both quantitatively and qualitatively different results between spread rate estimates. Accurate estimates of spread are dependent on how well the organism's spread mechanism follows the assumptions inherent in the model: violations of those assumptions can lead to high degrees of over- or under- estimation. For instance, despite being a good first approximation of spread (Andow et al. 1990; Grosholz 1996), the Skellam diffusion model (Shigesada, Kawasaki 1997) has shown to be an inappropriate estimator for organisms that rely on long distance human transport in dispersal – for the gypsy moth (Liebhold et al. 1992), cereal leaf beetle (Andow et al. 1990), and a variety of other species (Van den Bosch et al. 1992), the Skellam diffusion model produced underestimates of spread compared to observed spread rates. Failure to adhere to model assumptions can lead to breakdowns in a model's ability to predict spread rate.

One problem with estimating and comparing spread rates is that is not clear what exactly such estimators are meant to measure. There is no intrinsic biological spread rate. Rather the spread rate is an emergent property of ecological interactions, including human responses to invade damage and risk. As spread is measured *ex poste*, models must account for the complex suite of variables contributing to spread at the individual level. Dispersal is dependent on a large variety of factors including invader biology (dispersal mechanisms, reproductive rate, colonization patterns), environment (wind dispersal, habitat suitability), species interactions (competition, mutualism, predation), and human-species interactions (human transport, suppression). Not accounting for significant variables of spread may lead to an omitted variables bias and inaccurate spread rate estimations. Advances in the invasive species literature have grown to include more realistic spread patterns, complex species interactions, human-mediated transport, and environmental factors involved in spread (Hastings et al. 2005; Liebhold 2008), although most are contained within the theoretical spread literature. Efforts to breach the boundaries between the two fields are needed, taking the strengths of both and working towards a dynamic and effective spread estimator.

Spread estimation is not limited to the invasive species literature, but spans the fields of epidemiology and bioeconomics. Models that utilize estimates of spread to monitor populations in their analyses are subject to the same biases as other spread models. Caution needs to be taken when evaluating spread rates, as an effective estimator is highly dependent on the species and system in question.

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APPENDIX A

ODD PROTOCOL

Appendix A: ODD Protocol

I utilize the ODD (Overview, Design, concepts, and Detail) protocol to aid in the understanding of my model (Grimm et al. 2006; Grimm et al. 2010). The protocol was designed as a standardized publication description of agent-based models to facilitate communication, replication, and verification.

A.1 Purpose

The purpose of this model is to simulate the biological dispersal of an invasive insect pest and model its spread conditional on human behavior. The model is designed to generate dispersal data which is used in estimating spread rate by seven spread rate estimators chosen for their predominance in the literature.

My model was modified from a Wolfram predator-prey demonstration model, modeling the dynamics of fox predation on rabbit populations (Sayama 2012).

A.2 State variables and scales

The model contains three types of principle individuals or agents: Asian citrus psyllids (ACP), commercial citrus groves, and noncommercial citrus groves. Groves are assumed to have a unique owner with exclusive property rights. All agents possess their own x- and y-coordinate location. In addition, ACP agents have their own age (days), time since last feeding on citrus orchards (days), and indicator of agent type. ACP disperse independently (i.e. there are no density dependent factors affecting movement) and are assumed to be subject to starvation and a fixed maximum lifespan. Within an orchards, populations of sexually mature ACP agents reproduce according to geometric growth.

Orchard agents possess characteristics for orchard productivity, a binary management indicator, time within management period (days), and agent type indicator, and a behavior profile determining how an orchard manager responds to insect agents. Behavior profiles are analyst-specified and vary by orchard type. Similar orchard agent types have the same behavior profile within the model simulation. Orchard agents respond to insects independently of each other.

A.3 Process Overview and Scheduling

The model progresses in daily time steps. In order to simulate the invasion process, I run the simulation for two growing seasons (730 days). For each time step, the following occur in order: orchards detect ACP within their borders, ACP degrade orchard productivity ("feed"), orchards decide to administer a control treatment ("spray") according to their behavior profiles, ACP reproduce, ACP disperse, and ACP die. ACP that leave the environment (e.g. disperse past the border) are assumed to die.

At the end of every time step, location, age, and time since feeding are updated for ACP; orchards update their productivity level, indicator of management, and management level. Conditional on insects being alive in the environment, every seven time steps (week) the model uses the x, y locations of all ACP agents (dispersal data) to conduct six estimations of spread rate. A full description of spread estimations can be found in the Methods (p. 13). Orchard productivity and number of sprays are noted at the end of the first and second years. After the simulation has run its duration, all dispersal data is used to estimate a linear regression spread estimator and, for each of the other estimators, simulation spread estimates are averaged together producing an estimate of average spread.

A.4 Design Concepts

Basic principles

The model is designed to provide an approximation of the Asian citrus psyllid invasion in Southern California. I incorporate theories of ACP dispersal (Halbert, Manjunath 2004), human response (Hall et al. 2008; KAC 2012; Martin et al. 2009), and spread rate estimation (Hastings et al. 2005; Liebhold 2008).

Emergence

Spread emerges as a consequence of ACP dispersal and human response. As commercial orchards are supplied information about future spread or the state of infestation on their nearest neighbor's property, orchards may exhibit coordination in management.

Adaptation

In the base model neither ACP nor orchard agents experience adaptation.

Objectives

Orchard growers seek to maintain insect populations at or below their level of tolerance to insects.

Learning

Agents do not learn in my model, but orchards do react to forecasted insect spread in certain behavior profiles.

Prediction

Depending on the behavior profile (Table 2), orchards may predict future insect spread and respond in a preventative manner. Growers use two methods to predict spread: a radial estimate of spread rate, which predicts future insect population range, and observations of the state of infestation of the nearest neighbor's property, which indicates the probability of future infestation.

Sensing

Asian citrus psyllids detect citrus by a mix of olfactory and visual cues (Wenninger et al. 2008). Therefore, ACP agents are aware of the location of the closest orchard and disperse with a directional bias towards the center of the nearest orchard. Orchard agents are assumed to be able to detect numbers of all ACP within the orchard's borders.

Interaction

ACP agents interact with orchards to lower orchard productivity. Orchards interact with ACP by administering a treatment that lowers ACP populations within orchard borders.

Stochasticity

ACP dispersal is a stochastic process, with distance drawn from a gamma distribution and direction from a beta distribution. Each process uses an analyst-defined coefficient of variation and mean of distance between the ACP agent and the centroid of the nearest orchard to calculate the final dispersal location.

Collectives

ACP and orchard agents act independently of one another and do not act as collective organizations. However, due to emergent behavior, commercial growers may coordinate management of ACP, spraying at the same time according to forecasted spread or an interval spraying approach.

Observation

Average spread estimates are recorded at the end of the simulation, as is orchard productivity and numbers of sprays per orchard.

A.5 Initialization

At initialization, the model environment is loaded with the locations of commercial and noncommercial orchards preset according to the type of spatial configuration (Bakersfield or alternate). I include 214 commercial citrus orchards and 481 noncommercial orchards. Orchard agents are given behavior profiles based on their orchard type. Profiles for commercial and noncommercial orchards are determined by the treatment used in the model simulation. For a description of the behavior profiles used, see the Methods (p. 9). Technical spraying is assumed to operate with 90% efficiency with a duration of two months (Setamou et al. 2010).

100 ACP agents are randomly place at a point on the border of the environment; this location is the point of introduction or origin used in spread rate estimation. ACP agents are given a lifetime of 28 days, developmental time (egg to adult) of 16 days, starvation time of 4 days, and a daily intrinsic growth rate of 0.2 (Halbert, Manjunath 2004). Since ACP alone are a minor pest, feeding efficiency was derived such that in a no control setting ACP degrade orchard productivity by twenty percent in a year.

Dispersal coefficients of variation for distance traveled (drawn gamma distribution) and direction (beta distribution) are set to a combination of high (1.5 for the gamma, 0.9 for the beta) and low (0.5 for both) values.

A.6 Input Data

The model environment represents a 62 by 41 kilometer landscape. Using ArcGIS and the USDA's CropScape land use raster file (Weiguo et al. 2012), I approximate the quantity and location of commercial and residential (urban or noncommercial) citrus orchards in Bakersfield, CA to create the spatial configuration of commercial and noncommercial orchard agents. In order to decrease the number of agents, I restrict commercial growers to "Citrus" with an area greater than 74,000 square meters. Noncommercial orchards are limited to developed areas with "Medium" or "High" densities and an area greater than 50,000 square meters. Location was defined as the centroid of the GIS shape. Proportion of land-use is calculated for each orchard type and used to estimate the radius of each orchard. I assume that orchards of the same type are of equal size. The reader should note that the Bakersfield environment is meant to be an approximation of the actual California environment and not a map.

I define an analyst-generated alternative spatial layout as having the same proportion of land used by orchards as the Bakersfield environment, except orchards are randomly distributed across the landscape. Orchard x-y locations are drawn from normal distributions. Orchards possess the same radii as in the Bakersfield environment.

A7. Submodels

Orchard Degradation

ACP agents degrade citrus orchards according to a Holling Type-I response function given by:

$$y_{t+1} = y_t - a\, x_t\, y_t$$

where y_t indicates orchard productivity at time *t*, *a* denotes ACP feeding efficiency, and x_t the number of ACP within orchard borders at time *t*.

ACP Reproduction

When past the age of sexual maturity, ACP agents may reproduce if residing within a citrus orchard. ACP exhibit geometric growth where the number of new insects per time step is defined as:

$$x_n = a\, x_s$$

where x_n and x_s denote new and sexually mature insects, and *a* the daily intrinsic growth rate. Asian citrus psyllid reproduction and development is highly tied to temperature (Tsai, Liu 2000), but this feature is not incorporated in the nor do I include mating or multiple stages of development (e.g. egg, instar, nymph).

Technical Spray Efficiency

Spray efficiency is modeled as an exponential decay over time such that the spray initially exhibits full efficiency (α) then degrades to (1-α) by the end of the spray duration. Including reproduction and immigration, I effectively decrease insect populations to ten percent of their initial level. With a duration of two months, I calculate the current technical spray efficiency as:

$$E_t = \alpha\, e^{-0.0366\, d}$$

where E_t is the technical spray efficiency at time t, α the initial efficiency, and d the day since the initial treatment.

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APPENDIX B

AVERAGE SPREAD RATE TABLES:

BAKERSFIELD SPATIAL CONFIGURATION

Table B1. Average distance spread rate estimations for the Bakersfield orchard configuration with a low interval commercial treatment.

Mngmt. Strategy	Info. Structure	Biol. Param.	Linear Regression Spread Rate		Radial, Constant Spread Rate		Traveling Periodic Wave Speed	
			mean	st. error	mean	st. error	mean	st. error
3x/yr (c), 250 (n)	own property	1	0.209	0.060	17.638	0.590	12.899	0.371
3x/yr (c), 250 (n)	own property	2	0.309	0.077	18.422	0.241	15.530	0.206
3x/yr (c), 250 (n)	own property	3	0.000	0.008	3.266	0.109	5.559	0.131
3x/yr (c), 250 (n)	own property	4	3.271	0.217	25.028	0.228	19.541	0.221
3x/yr (c), 500 (n)	own property	1	0.015	0.005	0.982	0.035	0.876	0.024
3x/yr (c), 500 (n)	own property	2	0.301	0.079	18.274	0.237	15.379	0.194
3x/yr (c), 500 (n)	own property	3	0.049	0.002	0.489	0.010	0.805	0.018
3x/yr (c), 500 (n)	own property	4	3.262	0.226	24.793	0.227	19.367	0.205

(c) and (n) denote commercial and urban management strategies given as tolerance thresholds of ACP before spraying and interval spraying rates. Information structures include an orchard growers own property (op), expectations of future spread, and the state of their nearest neighbor's orchard. Biological parameters represent low mobility, high homing (1), high mobility, low homing (2), low mobility, low homing (3), and high mobility, high homing (4). Units of spread rate are in km/day.

Table B2. Average distance spread rate estimations (minimum and maximum bounds) for the Bakersfield orchard configuration with a low interval commercial treatment.

Mngmt. Strategy	**Info. Structure**	**Biol. Param.**	**Maximum Spread Rate**		**Minimum Spread Rate**	
			mean	**st. error**	**mean**	**st. error**
3x/yr (c), 250 (n)	own property	1	25.994	0.681	0.658	0.064
3x/yr (c), 250 (n)	own property	2	23.615	0.300	1.371	0.071
3x/yr (c), 250 (n)	own property	3	13.457	0.235	0.022	0.004
3x/yr (c), 250 (n)	own property	4	31.643	0.303	1.995	0.114
3x/yr (c), 500 (n)	own property	1	3.483	0.066	0.521	0.013
3x/yr (c), 500 (n)	own property	2	23.431	0.291	1.421	0.077
3x/yr (c), 500 (n)	own property	3	2.470	0.054	0.011	0.001
3x/yr (c), 500 (n)	own property	4	31.366	0.302	2.316	0.153

(c) and (n) denote commercial and urban management strategies given as tolerance thresholds of ACP before spraying and interval spraying rates. Information structures include an orchard growers own property (op), expectations of future spread, and the state of their nearest neighbor's orchard. Biological parameters represent low mobility, high homing (1), high mobility, low homing (2), low mobility, low homing (3), and high mobility, high homing (4). Units of spread rate are in km/day.

Table B3. Average distance spread rate estimations for the Bakersfield orchard configuration with a high interval commercial treatment.

Mngmt. Strategy	**Info. Structure**	**Biol. Param.**	**Linear Regression Spread Rate**		**Radial, Constant Spread Rate**		**Traveling Periodic Wave Speed**	
			mean	**st. error**	**mean**	**st. error**	**mean**	**st. error**
12x/yr (c), 250 (n)	own property	1	0.341	0.062	17.460	0.591	13.051	0.395
12x/yr (c), 250 (n)	own property	2	0.365	0.105	18.080	0.232	15.510	0.213
12x/yr (c), 250 (n)	own property	3	0.032	0.007	3.853	0.203	6.033	0.187
12x/yr (c), 250 (n)	own property	4	4.247	0.278	25.345	0.222	20.075	0.235
12x/yr (c), 500 (n)	own property	1	0.288	0.059	17.243	0.586	12.988	0.409
12x/yr (c), 500 (n)	own property	2	0.374	0.133	14.554	0.260	14.990	0.232
12x/yr (c), 500 (n)	own property	3	0.035	0.007	3.357	0.209	5.475	0.190
12x/yr (c), 500 (n)	own property	4	2.524	0.311	19.003	0.256	18.606	0.279

(c) and (n) denote commercial and urban management strategies given as tolerance thresholds of ACP before spraying and interval spraying rates. Information structures include an orchard growers own property (op), expectations of future spread, and the state of their nearest neighbor's orchard. Biological parameters represent low mobility, high homing (1), high mobility, low homing (2), low mobility, low homing (3), and high mobility, high homing (4). Units of spread rate are in km/day.

Table B4. Average distance spread rate estimations (minimum and maximum bounds) for the Bakersfield orchard configuration with a high interval commercial treatment.

Mngmt. Strategy	**Info. Structure**	**Biol. Param.**	**Maximum Spread Rate**		**Minimum Spread Rate**	
			mean	**st. error**	**mean**	**st. error**
12x/yr (c), 250 (n)	own property	1	25.626	0.656	0.612	0.058
12x/yr (c), 250 (n)	own property	2	23.032	0.280	1.366	0.092
12x/yr (c), 250 (n)	own property	3	13.719	0.262	0.024	0.003
12x/yr (c), 250 (n)	own property	4	31.933	0.304	2.252	0.129
12x/yr (c), 500 (n)	own property	1	25.372	0.677	0.663	0.053
12x/yr (c), 500 (n)	own property	2	18.717	0.325	1.175	0.063
12x/yr (c), 500 (n)	own property	3	13.204	0.269	0.018	0.002
12x/yr (c), 500 (n)	own property	4	23.902	0.321	2.359	0.153

(c) and (n) denote commercial and urban management strategies given as tolerance thresholds of ACP before spraying and interval spraying rates. Information structures include an orchard growers own property (op), expectations of future spread, and the state of their nearest neighbor's orchard. Biological parameters represent low mobility, high homing (1), high mobility, low homing (2), low mobility, low homing (3), and high mobility, high homing (4). Units of spread rate are in km/day.

Table B5. Average distance spread rate estimations for the Bakersfield orchard configuration with a low commercial, low noncommercial threshold treatment.

Mngmt. Strategy	**Info. Structure**	**Biol. Param.**	**Linear Regression Spread Rate**		**Radial, Constant Spread Rate**		**Traveling Periodic Wave Speed**	
			mean	**st. error**	**mean**	**st. error**	**mean**	**st. error**
150 (c), 250 (n)	own property	1	0.728	0.085	25.672	0.255	19.984	0.199
150 (c), 250 (n)	own property	2	0.291	0.126	13.435	0.151	14.739	0.167
150 (c), 250 (n)	own property	3	-0.013	0.018	7.843	0.384	8.955	0.305
150 (c), 250 (n)	own property	4	3.171	0.285	19.705	0.242	19.194	0.253
150 (c), 250 (n)	op + expectation	1	0.234	0.069	16.857	0.455	12.717	0.391
150 (c), 250 (n)	op + expectation	2	0.155	0.142	16.425	0.158	17.156	0.139
150 (c), 250 (n)	op + expectation	3	-0.045	0.009	7.003	0.334	8.399	0.296
150 (c), 250 (n)	op + expectation	4	3.212	0.285	19.382	0.266	18.952	0.250
150 (c), 250 (n)	op + neighbor	1	1.625	0.112	25.344	0.336	19.524	0.236
150 (c), 250 (n)	op + neighbor	2	0.887	0.148	15.822	0.190	17.535	0.209
150 (c), 250 (n)	op + neighbor	3	-0.035	0.008	7.754	0.357	9.002	0.312
150 (c), 250 (n)	op + neighbor	4	3.016	0.294	19.362	0.249	19.040	0.277

(c) and (n) denote commercial and urban management strategies given as tolerance thresholds of ACP before spraying. Information structures include an orchard growers own property (op), expectations of future spread, and the state of their nearest neighbor's orchard. Biological parameters represent low mobility, high homing (1), high mobility, low homing (2), low mobility, low homing (3), and high mobility, high homing (4). Units of spread rate are in km/day.

Table B6. Average distance spread rate estimations (minimum and maximum bounds) for the Bakersfield orchard configuration with a low commercial, low noncommercial threshold treatment.

Mngmt. Strategy	**Info. Structure**	**Biol. Param.**	**Maximum Spread Rate**		**Minimum Spread Rate**	
			mean	**st. error**	**mean**	**st. error**
150 (c), 250 (n)	own property	1	33.784	0.357	0.899	0.066
150 (c), 250 (n)	own property	2	17.267	0.194	1.250	0.075
150 (c), 250 (n)	own property	3	14.746	0.394	0.068	0.009
150 (c), 250 (n)	own property	4	24.995	0.323	2.528	0.161
150 (c), 250 (n)	op + expectation	1	22.583	0.560	0.845	0.069
150 (c), 250 (n)	op + expectation	2	20.943	0.215	1.296	0.081
150 (c), 250 (n)	op + expectation	3	13.676	0.365	0.087	0.012
150 (c), 250 (n)	op + expectation	4	24.649	0.345	2.237	0.157
150 (c), 250 (n)	op + neighbor	1	33.383	0.423	1.121	0.092
150 (c), 250 (n)	op + neighbor	2	20.305	0.223	1.369	0.084
150 (c), 250 (n)	op + neighbor	3	14.507	0.370	0.070	0.009
150 (c), 250 (n)	op + neighbor	4	24.506	0.328	1.821	0.125

(c) and (n) denote commercial and urban management strategies given as tolerance thresholds of ACP before spraying. Information structures include an orchard growers own property (op), expectations of future spread, and the state of their nearest neighbor's orchard. Biological parameters represent low mobility, high homing (1), high mobility, low homing (2), low mobility, low homing (3), and high mobility, high homing (4). Units of spread rate are in km/day.

Table B7. Average distance spread rate estimations for the Bakersfield orchard configuration with a low commercial, high noncommercial threshold treatment.

Mngmt. Strategy	**Info. Structure**	**Biol. Param.**	**Linear Regression Spread Rate**		**Radial, Constant Spread Rate**		**Traveling Periodic Wave Speed**	
			mean	**st. error**	**mean**	**st. error**	**mean**	**st. error**
150 (c), 500 (n)	own property	1	0.691	0.092	22.590	0.288	16.744	0.182
150 (c), 500 (n)	own property	2	0.984	0.181	16.731	0.204	17.887	0.188
150 (c), 500 (n)	own property	3	-0.032	0.009	7.164	0.357	8.475	0.315
150 (c), 500 (n)	own property	4	3.081	0.289	19.306	0.249	18.860	0.263
150 (c), 500 (n)	op + expectation	1	1.038	0.096	19.857	0.398	14.837	0.288
150 (c), 500 (n)	op + expectation	2	0.505	0.141	14.905	0.159	15.559	0.125
150 (c), 500 (n)	op + expectation	3	-0.013	0.008	8.232	0.388	9.379	0.320
150 (c), 500 (n)	op + expectation	4	2.784	0.288	19.461	0.270	18.883	0.275
150 (c), 500 (n)	op + neighbor	1	0.826	0.094	23.555	0.292	17.795	0.235
150 (c), 500 (n)	op + neighbor	2	0.318	0.116	12.751	0.336	13.879	0.386
150 (c), 500 (n)	op + neighbor	3	-0.018	0.006	7.314	0.347	8.439	0.297
150 (c), 500 (n)	op + neighbor	4	3.019	0.295	19.636	0.250	19.038	0.259

(c) and (n) denote commercial and urban management strategies given as tolerance thresholds of ACP before spraying. Information structures include an orchard growers own property (op), expectations of future spread, and the state of their nearest neighbor's orchard. Biological parameters represent low mobility, high homing (1), high mobility, low homing (2), low mobility, low homing (3), and high mobility, high homing (4). Units of spread rate are in km/day.

Table B8. Average distance spread rate estimations (minimum and maximum bounds) for the Bakersfield orchard configuration with a low commercial, high noncommercial threshold treatment.

Mngmt. Strategy	**Info. Structure**	**Biol. Param.**	**Maximum Spread Rate**		**Minimum Spread Rate**	
			mean	**st. error**	**mean**	**st. error**
150 (c), 500 (n)	own property	1	29.627	0.371	1.006	0.098
150 (c), 500 (n)	own property	2	21.345	0.240	1.330	0.078
150 (c), 500 (n)	own property	3	14.037	0.368	0.074	0.008
150 (c), 500 (n)	own property	4	24.404	0.334	2.321	0.151
150 (c), 500 (n)	op + expectation	1	26.352	0.518	0.852	0.071
150 (c), 500 (n)	op + expectation	2	18.946	0.200	1.243	0.077
150 (c), 500 (n)	op + expectation	3	15.071	0.392	0.085	0.010
150 (c), 500 (n)	op + expectation	4	24.584	0.338	2.148	0.154
150 (c), 500 (n)	op + neighbor	1	30.984	0.376	1.059	0.083
150 (c), 500 (n)	op + neighbor	2	16.580	0.408	1.141	0.062
150 (c), 500 (n)	op + neighbor	3	14.203	0.413	0.081	0.014
150 (c), 500 (n)	op + neighbor	4	24.813	0.339	2.318	0.159

(c) and (n) denote commercial and urban management strategies given as tolerance thresholds of ACP before spraying. Information structures include an orchard growers own property (op), expectations of future spread, and the state of their nearest neighbor's orchard. Biological parameters represent low mobility, high homing (1), high mobility, low homing (2), low mobility, low homing (3), and high mobility, high homing (4). Units of spread rate are in km/day.

Table B9. Average distance spread rate estimations for the Bakersfield orchard configuration with a high commercial, high noncommercial threshold treatment.

Mngmt. Strategy	Info. Structure	Biol. Param.	Linear Regression Spread Rate		Radial, Constant Spread Rate		Traveling Periodic Wave Speed	
			mean	st. error	mean	st. error	mean	st. error
250 (c), 500 (n)	own property	1	0.485	0.081	24.154	0.340	18.969	0.311
250 (c), 500 (n)	own property	2	0.245	0.133	15.455	0.187	16.132	0.166
250 (c), 500 (n)	own property	3	-0.033	0.008	8.120	0.390	9.209	0.316
250 (c), 500 (n)	own property	4	2.803	0.288	19.756	0.251	19.157	0.264
250 (c), 500 (n)	op + expectation	1	1.120	0.090	20.233	0.422	14.723	0.301
250 (c), 500 (n)	op + expectation	2	0.842	0.155	15.522	0.183	16.405	0.150
250 (c), 500 (n)	op + expectation	3	-0.035	0.008	7.970	0.371	9.076	0.328
250 (c), 500 (n)	op + expectation	4	3.519	0.305	19.625	0.265	18.873	0.285
250 (c), 500 (n)	op + neighbor	1	0.956	0.114	22.747	0.303	17.967	0.203
250 (c), 500 (n)	op + neighbor	2	0.581	0.150	16.007	0.227	17.634	0.251
250 (c), 500 (n)	op + neighbor	3	-0.021	0.007	7.313	0.368	8.492	0.311
250 (c), 500 (n)	op + neighbor	4	2.338	0.262	16.074	0.384	16.095	0.346

(c) and (n) denote commercial and urban management strategies given as tolerance thresholds of ACP before spraying. Information structures include an orchard growers own property (op), expectations of future spread, and the state of their nearest neighbor's orchard. Biological parameters represent low mobility, high homing (1), high mobility, low homing (2), low mobility, low homing (3), and high mobility, high homing (4). Units of spread rate are in km/day.

Table B10. Average distance spread rate estimations (minimum and maximum bounds) for the Bakersfield orchard configuration with a high commercial, high noncommercial threshold treatment.

Mngmt. Strategy	**Info. Structure**	**Biol. Param.**	**Maximum Spread Rate**		**Minimum Spread Rate**	
			mean	**st. error**	**mean**	**st. error**
250 (c), 500 (n)	own property	1	31.684	0.450	0.873	0.066
250 (c), 500 (n)	own property	2	19.678	0.238	1.214	0.060
250 (c), 500 (n)	own property	3	14.932	0.402	0.068	0.009
250 (c), 500 (n)	own property	4	24.966	0.334	2.217	0.152
250 (c), 500 (n)	op + expectation	1	26.992	0.528	1.114	0.094
250 (c), 500 (n)	op + expectation	2	19.763	0.230	1.214	0.074
250 (c), 500 (n)	op + expectation	3	14.805	0.397	0.093	0.012
250 (c), 500 (n)	op + expectation	4	24.957	0.339	2.106	0.134
250 (c), 500 (n)	op + neighbor	1	29.842	0.404	1.283	0.090
250 (c), 500 (n)	op + neighbor	2	20.431	0.282	1.129	0.072
250 (c), 500 (n)	op + neighbor	3	14.303	0.379	0.083	0.015
250 (c), 500 (n)	op + neighbor	4	21.791	0.392	1.643	0.136

(c) and (n) denote commercial and urban management strategies given as tolerance thresholds of ACP before spraying. Information structures include an orchard growers own property (op), expectations of future spread, and the state of their nearest neighbor's orchard. Biological parameters represent low mobility, high homing (1), high mobility, low homing (2), low mobility, low homing (3), and high mobility, high homing (4). Units of spread rate are in km/day.

Table B11. Average population front spread estimations for the Bakersfield orchard configuration with a low interval commercial treatment.

Mngmt. Strategy	Info. Structure	Biol. Param.	Δ Radial Population Front		Δ Cardinal Directions (NSEW)	
			mean	st. error	mean	st. error
3x/yr (c), 250 (n)	own property	1	60.524	2.785	6.768	0.231
3x/yr (c), 250 (n)	own property	2	63.455	1.030	11.329	0.157
3x/yr (c), 250 (n)	own property	3	4.957	0.424	1.380	0.059
3x/yr (c), 250 (n)	own property	4	83.054	1.187	11.762	0.119
3x/yr (c), 500 (n)	own property	1	0.688	0.095	1.063	0.034
3x/yr (c), 500 (n)	own property	2	63.029	1.002	11.266	0.148
3x/yr (c), 500 (n)	own property	3	0.581	0.015	1.065	0.033
3x/yr (c), 500 (n)	own property	4	82.131	1.228	11.763	0.123

(c) and (n) denote commercial and urban management strategies given as tolerance thresholds of ACP before spraying. Information structures include an orchard growers own property (op), expectations of future spread, and the state of their nearest neighbor's orchard. Biological parameters represent low mobility, high homing (1), high mobility, low homing (2), low mobility, low homing (3), and high mobility, high homing (4). Units of spread rate are in km/day.

Table B12. Average population front spread estimations for the Bakersfield orchard configuration with a high interval commercial treatment.

Mngmt. Strategy	**Info. Structure**	**Biol. Param.**	**Δ Radial Population Front**		**Δ Cardinal Directions (NSEW)**	
			mean	**st. error**	**mean**	**st. error**
12x/yr (c), 250 (n)	own property	1	58.803	2.674	6.904	0.249
12x/yr (c), 250 (n)	own property	2	60.154	1.031	11.109	0.166
12x/yr (c), 250 (n)	own property	3	8.431	0.868	1.847	0.132
12x/yr (c), 250 (n)	own property	4	82.793	1.231	11.218	0.123
12x/yr (c), 500 (n)	own property	1	58.142	2.578	6.825	0.253
12x/yr (c), 500 (n)	own property	2	49.176	1.077	10.902	0.182
12x/yr (c), 500 (n)	own property	3	7.847	0.897	1.649	0.141
12x/yr (c), 500 (n)	own property	4	61.563	1.165	11.068	0.147

(c) and (n) denote commercial and urban management strategies given as tolerance thresholds of ACP before spraying. Information structures include an orchard growers own property (op), expectations of future spread, and the state of their nearest neighbor's orchard. Biological parameters represent low mobility, high homing (1), high mobility, low homing (2), low mobility, low homing (3), and high mobility, high homing (4). Units of spread rate are in km/day.

Table B13. Average population front spread estimations for the Bakersfield orchard configuration with a low commercial, low noncommercial threshold treatment.

Mngmt. Strategy	**Info. Structure**	**Biol. Param.**	**Δ Radial Population Front**		**Δ Cardinal Directions (NSEW)**	
			mean	**st. error**	**mean**	**st. error**
150 (c), 250 (n)	own property	1	101.392	1.177	12.620	0.077
150 (c), 250 (n)	own property	2	48.152	0.680	11.218	0.144
150 (c), 250 (n)	own property	3	28.418	1.718	5.413	0.267
150 (c), 250 (n)	own property	4	66.474	1.191	11.559	0.132
150 (c), 250 (n)	op + expectation	1	62.136	1.948	9.967	0.192
150 (c), 250 (n)	op + expectation	2	56.777	0.794	12.550	0.172
150 (c), 250 (n)	op + expectation	3	24.230	1.554	5.000	0.259
150 (c), 250 (n)	op + expectation	4	66.195	1.263	11.344	0.148
150 (c), 250 (n)	op + neighbor	1	98.468	1.496	12.772	0.113
150 (c), 250 (n)	op + neighbor	2	56.332	0.794	12.390	0.148
150 (c), 250 (n)	op + neighbor	3	27.690	1.676	5.614	0.268
150 (c), 250 (n)	op + neighbor	4	64.639	1.278	11.372	0.141

(c) and (n) denote commercial and urban management strategies given as tolerance thresholds of ACP before spraying. Information structures include an orchard growers own property (op), expectations of future spread, and the state of their nearest neighbor's orchard. Biological parameters represent low mobility, high homing (1), high mobility, low homing (2), low mobility, low homing (3), and high mobility, high homing (4). Units of spread rate are in km/day.

Table B14. Average population front spread estimations for the Bakersfield orchard configuration with a low commercial, high noncommercial threshold treatment.

Mngmt. Strategy	Info. Structure	Biol. Param.	Δ Radial Population Front		Δ Cardinal Directions (NSEW)	
			mean	st. error	mean	st. error
150 (c), 500 (n)	own property	1	85.889	1.369	12.155	0.105
150 (c), 500 (n)	own property	2	57.984	0.858	12.377	0.112
150 (c), 500 (n)	own property	3	25.935	1.702	5.083	0.277
150 (c), 500 (n)	own property	4	64.061	1.225	11.576	0.136
150 (c), 500 (n)	op + expectation	1	76.131	1.830	11.963	0.173
150 (c), 500 (n)	op + expectation	2	50.774	0.641	12.509	0.128
150 (c), 500 (n)	op + expectation	3	30.588	1.727	5.941	0.290
150 (c), 500 (n)	op + expectation	4	64.382	1.277	11.158	0.144
150 (c), 500 (n)	op + neighbor	1	91.375	1.371	10.963	0.161
150 (c), 500 (n)	op + neighbor	2	43.980	1.289	10.839	0.266
150 (c), 500 (n)	op + neighbor	3	26.740	1.647	5.176	0.286
150 (c), 500 (n)	op + neighbor	4	65.048	1.212	11.491	0.140

(c) and (n) denote commercial and urban management strategies given as tolerance thresholds of ACP before spraying. Information structures include an orchard growers own property (op), expectations of future spread, and the state of their nearest neighbor's orchard. Biological parameters represent low mobility, high homing (1), high mobility, low homing (2), low mobility, low homing (3), and high mobility, high homing (4). Units of spread rate are in km/day.

Table B15. Average population front spread estimations for the Bakersfield orchard configuration with a high commercial, high noncommercial threshold treatment.

Mngmt. Strategy	**Info. Structure**	**Biol. Param.**	**Δ Radial Population Front**		**Δ Cardinal Directions (NSEW)**	
			mean	**st. error**	**mean**	**st. error**
250 (c), 500 (n)	own property	1	93.245	1.477	11.908	0.096
250 (c), 500 (n)	own property	2	53.066	0.787	12.689	0.132
250 (c), 500 (n)	own property	3	30.044	1.738	5.843	0.275
250 (c), 500 (n)	own property	4	65.477	1.304	11.445	0.139
250 (c), 500 (n)	op + expectation	1	78.188	1.828	10.374	0.192
250 (c), 500 (n)	op + expectation	2	53.302	0.706	12.108	0.106
250 (c), 500 (n)	op + expectation	3	29.352	1.670	5.680	0.282
250 (c), 500 (n)	op + expectation	4	66.941	1.221	11.288	0.135
250 (c), 500 (n)	op + neighbor	1	87.032	1.444	11.647	0.139
250 (c), 500 (n)	op + neighbor	2	55.589	0.883	10.901	0.196
250 (c), 500 (n)	op + neighbor	3	26.395	1.660	4.983	0.260
250 (c), 500 (n)	op + neighbor	4	53.584	1.585	9.569	0.226

(c) and (n) denote commercial and urban management strategies given as tolerance thresholds of ACP before spraying. Information structures include an orchard growers own property (op), expectations of future spread, and the state of their nearest neighbor's orchard. Biological parameters represent low mobility, high homing (1), high mobility, low homing (2), low mobility, low homing (3), and high mobility, high homing (4). Units of spread rate are in km/day.

APPENDIX C

AVERAGE SPREAD RATE TABLES:

ALTERNATE SPATIAL CONFIGURATION

Table C1. Average distance spread rate estimations for the alternate orchard configuration with a low interval commercial treatment.

Mngmt. Strategy	**Info. Structure**	**Biol. Param.**	**Linear Regression Spread Rate**		**Radial, Constant Spread Rate**		**Traveling Periodic Wave Speed**	
			mean	**st. error**	**mean**	**st. error**	**mean**	**st. error**
3x/yr (c), 250 (n)	own property	1	0.005	0.005	1.206	0.035	1.001	0.025
3x/yr (c), 250 (n)	own property	2	0.078	0.014	2.312	0.087	1.842	0.065
3x/yr (c), 250 (n)	own property	3	0.063	0.002	0.617	0.012	0.901	0.020
3x/yr (c), 250 (n)	own property	4	0.655	0.054	7.145	0.182	3.555	0.088
3x/yr (c), 500 (n)	own property	1	0.017	0.005	0.986	0.042	0.880	0.027
3x/yr (c), 500 (n)	own property	2	0.131	0.018	2.668	0.091	2.110	0.066
3x/yr (c), 500 (n)	own property	3	0.051	0.002	0.472	0.010	0.770	0.017
3x/yr (c), 500 (n)	own property	4	0.699	0.052	7.384	0.199	3.588	0.092

(c) and (n) denote commercial and urban management strategies given as tolerance thresholds of ACP before spraying and interval spraying rates. Information structures include an orchard growers own property (op), expectations of future spread, and the state of their nearest neighbor's orchard. Biological parameters represent low mobility, high homing (1), high mobility, low homing (2), low mobility, low homing (3), and high mobility, high homing (4). Units of spread rate are in km/day.

Table C2. Average distance spread rate estimations (minimum and maximum bounds) for the alternate orchard configuration with a low interval commercial treatment.

Mngmt. Strategy	**Info. Structure**	**Biol. Param.**	**Maximum Spread Rate**		**Minimum Spread Rate**	
			mean	**st. error**	**mean**	**st. error**
3x/yr (c), 250 (n)	own property	1	3.629	0.066	0.427	0.014
3x/yr (c), 250 (n)	own property	2	4.004	0.090	0.833	0.027
3x/yr (c), 250 (n)	own property	3	2.506	0.056	0.016	0.001
3x/yr (c), 250 (n)	own property	4	9.561	0.197	1.647	0.070
3x/yr (c), 500 (n)	own property	1	3.487	0.074	0.524	0.013
3x/yr (c), 500 (n)	own property	2	4.383	0.087	0.864	0.030
3x/yr (c), 500 (n)	own property	3	2.374	0.054	0.011	0.001
3x/yr (c), 500 (n)	own property	4	10.061	0.202	1.866	0.081

(c) and (n) denote commercial and urban management strategies given as tolerance thresholds of ACP before spraying and interval spraying rates. Information structures include an orchard growers own property (op), expectations of future spread, and the state of their nearest neighbor's orchard. Biological parameters represent low mobility, high homing (1), high mobility, low homing (2), low mobility, low homing (3), and high mobility, high homing (4). Units of spread rate are in km/day.

Table C3. Average distance spread rate estimations for the alternate orchard configuration with a high interval commercial treatment.

Mngmt. Strategy	Info. Structure	Biol. Param.	Linear Regression Spread Rate		Radial, Constant Spread Rate		Traveling Periodic Wave Speed	
			mean	st. error	mean	st. error	mean	st. error
12x/yr (c), 250 (n)	own property	1	0.038	0.008	1.348	0.059	1.081	0.031
12x/yr (c), 250 (n)	own property	2	0.116	0.017	2.349	0.088	1.861	0.062
12x/yr (c), 250 (n)	own property	3	0.054	0.002	0.604	0.015	0.918	0.021
12x/yr (c), 250 (n)	own property	4	0.723	0.054	7.237	0.175	3.558	0.085
12x/yr (c), 500 (n)	own property	1	0.044	0.008	1.132	0.059	0.957	0.032
12x/yr (c), 500 (n)	own property	2	0.112	0.017	2.373	0.091	1.911	0.066
12x/yr (c), 500 (n)	own property	3	0.047	0.002	0.483	0.012	0.805	0.019
12x/yr (c), 500 (n)	own property	4	0.844	0.065	7.503	0.170	3.759	0.088

(c) and (n) denote commercial and urban management strategies given as tolerance thresholds of ACP before spraying and interval spraying rates. Information structures include an orchard growers own property (op), expectations of future spread, and the state of their nearest neighbor's orchard. Biological parameters represent low mobility, high homing (1), high mobility, low homing (2), low mobility, low homing (3), and high mobility, high homing (4). Units of spread rate are in km/day.

Table C4. Average distance spread rate estimations (minimum and maximum bounds) for the alternate orchard configuration with a high interval commercial treatment.

Mngmt. Strategy	Info. Structure	Biol. Param.	Maximum Spread Rate		Minimum Spread Rate	
			mean	st. error	mean	st. error
12x/yr (c), 250 (n)	own property	1	3.789	0.081	0.429	0.020
12x/yr (c), 250 (n)	own property	2	3.980	0.090	0.837	0.029
12x/yr (c), 250 (n)	own property	3	2.433	0.058	0.020	0.003
12x/yr (c), 250 (n)	own property	4	9.541	0.183	1.739	0.075
12x/yr (c), 500 (n)	own property	1	3.634	0.083	0.537	0.021
12x/yr (c), 500 (n)	own property	2	4.075	0.088	0.829	0.026
12x/yr (c), 500 (n)	own property	3	2.396	0.055	0.014	0.002
12x/yr (c), 500 (n)	own property	4	9.936	0.184	1.873	0.083

(c) and (n) denote commercial and urban management strategies given as tolerance thresholds of ACP before spraying and interval spraying rates. Information structures include an orchard growers own property (op), expectations of future spread, and the state of their nearest neighbor's orchard. Biological parameters represent low mobility, high homing (1), high mobility, low homing (2), low mobility, low homing (3), and high mobility, high homing (4). Units of spread rate are in km/day.

Table C5. Average distance spread rate estimations for the alternate orchard configuration with a low commercial, low noncommercial threshold treatment.

Mngmt. Strategy	**Info. Structure**	**Biol. Param.**	**Linear Regression Spread Rate**		**Radial, Constant Spread Rate**		**Traveling Periodic Wave Speed**	
			mean	**st. error**	**mean**	**st. error**	**mean**	**st. error**
150 (c), 250 (n)	own property	1	0.051	0.003	1.024	0.020	0.895	0.016
150 (c), 250 (n)	own property	2	0.481	0.054	6.977	0.187	6.354	0.204
150 (c), 250 (n)	own property	3	0.071	0.002	0.609	0.011	0.928	0.019
150 (c), 250 (n)	own property	4	0.709	0.058	7.618	0.165	3.750	0.085
150 (c), 250 (n)	op + expectation	1	0.042	0.002	0.853	0.012	0.620	0.010
150 (c), 250 (n)	op + expectation	2	-0.157	0.077	4.408	0.230	3.704	0.203
150 (c), 250 (n)	op + expectation	3	0.059	0.002	0.599	0.012	0.858	0.020
150 (c), 250 (n)	op + expectation	4	0.699	0.058	7.326	0.175	3.669	0.084
150 (c), 250 (n)	op + neighbor	1	0.005	0.004	1.185	0.023	1.031	0.018
150 (c), 250 (n)	op + neighbor	2	0.045	0.010	1.855	0.085	1.599	0.076
150 (c), 250 (n)	op + neighbor	3	0.067	0.002	0.609	0.011	0.918	0.019
150 (c), 250 (n)	op + neighbor	4	0.660	0.050	7.166	0.184	3.510	0.085

(c) and (n) denote commercial and urban management strategies given as tolerance thresholds of ACP before spraying and interval spraying rates. Information structures include an orchard growers own property (op), expectations of future spread, and the state of their nearest neighbor's orchard. Biological parameters represent low mobility, high homing (1), high mobility, low homing (2), low mobility, low homing (3), and high mobility, high homing (4). Units of spread rate are in km/day.

Table C6. Average distance spread rate estimations (minimum and maximum bounds) for the alternate orchard configuration with a low commercial, low noncommercial threshold treatment.

Mngmt. Strategy	**Info. Structure**	**Biol. Param.**	**Maximum Spread Rate**		**Minimum Spread Rate**	
			mean	**st. error**	**mean**	**st. error**
150 (c), 250 (n)	own property	1	3.526	0.049	0.421	0.012
150 (c), 250 (n)	own property	2	9.242	0.233	1.041	0.050
150 (c), 250 (n)	own property	3	2.651	0.056	0.014	0.001
150 (c), 250 (n)	own property	4	9.985	0.186	1.767	0.080
150 (c), 250 (n)	op + expectation	1	2.766	0.037	0.450	0.012
150 (c), 250 (n)	op + expectation	2	6.166	0.275	0.825	0.042
150 (c), 250 (n)	op + expectation	3	2.389	0.056	0.017	0.001
150 (c), 250 (n)	op + expectation	4	9.707	0.193	1.637	0.073
150 (c), 250 (n)	op + neighbor	1	3.467	0.053	0.308	0.012
150 (c), 250 (n)	op + neighbor	2	3.552	0.094	0.835	0.024
150 (c), 250 (n)	op + neighbor	3	2.569	0.056	0.014	0.001
150 (c), 250 (n)	op + neighbor	4	9.644	0.189	1.692	0.066

(c) and (n) denote commercial and urban management strategies given as tolerance thresholds of ACP before spraying and interval spraying rates. Information structures include an orchard growers own property (op), expectations of future spread, and the state of their nearest neighbor's orchard. Biological parameters represent low mobility, high homing (1), high mobility, low homing (2), low mobility, low homing (3), and high mobility, high homing (4). Units of spread rate are in km/day.

Table C7. Average distance spread rate estimations for the alternate orchard configuration with a low commercial, high noncommercial threshold treatment.

Mngmt. Strategy	**Info. Structure**	**Biol. Param.**	**Linear Regression Spread Rate**		**Radial, Constant Spread Rate**		**Traveling Periodic Wave Speed**	
			mean	**st. error**	**mean**	**st. error**	**mean**	**st. error**
150 (c), 500 (n)	own property	1	0.029	0.003	0.955	0.021	0.919	0.015
150 (c), 500 (n)	own property	2	0.013	0.019	2.372	0.085	1.725	0.054
150 (c), 500 (n)	own property	3	0.055	0.002	0.474	0.009	0.793	0.016
150 (c), 500 (n)	own property	4	0.696	0.047	7.377	0.189	3.567	0.086
150 (c), 500 (n)	op + expectation	1	0.038	0.044	7.313	0.526	6.857	0.496
150 (c), 500 (n)	op + expectation	2	0.086	0.015	3.237	0.107	2.653	0.085
150 (c), 500 (n)	op + expectation	3	0.049	0.002	0.487	0.010	0.787	0.018
150 (c), 500 (n)	op + expectation	4	0.749	0.052	7.501	0.197	3.649	0.094
150 (c), 500 (n)	op + neighbor	1	0.017	0.003	0.972	0.016	0.742	0.019
150 (c), 500 (n)	op + neighbor	2	0.187	0.018	2.179	0.096	1.674	0.068
150 (c), 500 (n)	op + neighbor	3	0.592	0.050	7.226	0.185	3.484	0.085
150 (c), 500 (n)	op + neighbor	4	0.647	0.046	7.477	0.167	3.644	0.079

(c) and (n) denote commercial and urban management strategies given as tolerance thresholds of ACP before spraying and interval spraying rates. Information structures include an orchard growers own property (op), expectations of future spread, and the state of their nearest neighbor's orchard. Biological parameters represent low mobility, high homing (1), high mobility, low homing (2), low mobility, low homing (3), and high mobility, high homing (4). Units of spread rate are in km/day.

Table C8. Average distance spread rate estimations (minimum and maximum bounds) for the alternate orchard configuration with a low commercial, high noncommercial threshold treatment.

Mngmt. Strategy	**Info. Structure**	**Biol. Param.**	**Maximum Spread Rate**		**Minimum Spread Rate**	
			mean	**st. error**	**mean**	**st. error**
150 (c), 500 (n)	own property	1	3.571	0.046	0.482	0.013
150 (c), 500 (n)	own property	2	3.931	0.080	0.787	0.025
150 (c), 500 (n)	own property	3	2.466	0.055	0.011	0.001
150 (c), 500 (n)	own property	4	9.947	0.206	1.743	0.077
150 (c), 500 (n)	op + expectation	1	10.887	0.657	0.609	0.035
150 (c), 500 (n)	op + expectation	2	4.940	0.105	0.951	0.030
150 (c), 500 (n)	op + expectation	3	2.397	0.059	0.014	0.001
150 (c), 500 (n)	op + expectation	4	10.064	0.213	1.796	0.103
150 (c), 500 (n)	op + neighbor	1	3.322	0.055	0.557	0.014
150 (c), 500 (n)	op + neighbor	2	3.863	0.101	0.932	0.027
150 (c), 500 (n)	op + neighbor	3	9.737	0.206	1.707	0.071
150 (c), 500 (n)	op + neighbor	4	9.845	0.183	1.584	0.077

(c) and (n) denote commercial and urban management strategies given as tolerance thresholds of ACP before spraying and interval spraying rates. Information structures include an orchard growers own property (op), expectations of future spread, and the state of their nearest neighbor's orchard. Biological parameters represent low mobility, high homing (1), high mobility, low homing (2), low mobility, low homing (3), and high mobility, high homing (4). Units of spread rate are in km/day.

Table C9. Average distance spread rate estimations for the alternate orchard configuration with a high commercial, high noncommercial threshold treatment.

Mngmt. Strategy	**Info. Structure**	**Biol. Param.**	**Linear Regression Spread Rate**		**Radial, Constant Spread Rate**		**Traveling Periodic Wave Speed**	
			mean	**st. error**	**mean**	**st. error**	**mean**	**st. error**
250 (c), 500 (n)	own property	1	0.019	0.004	1.016	0.032	0.803	0.025
250 (c), 500 (n)	own property	2	0.189	0.016	2.597	0.096	2.201	0.069
250 (c), 500 (n)	own property	3	0.054	0.002	0.474	0.009	0.786	0.018
250 (c), 500 (n)	own property	4	0.684	0.055	7.290	0.175	3.573	0.083
250 (c), 500 (n)	op + expectation	1	0.028	0.003	0.897	0.012	0.803	0.009
250 (c), 500 (n)	op + expectation	2	0.000	0.009	1.584	0.067	1.358	0.043
250 (c), 500 (n)	op + expectation	3	0.051	0.002	0.489	0.009	0.802	0.018
250 (c), 500 (n)	op + expectation	4	0.678	0.057	7.377	0.194	3.554	0.092
250 (c), 500 (n)	op + neighbor	1	0.024	0.003	1.023	0.018	0.979	0.018
250 (c), 500 (n)	op + neighbor	2	0.093	0.012	2.622	0.087	1.990	0.050
250 (c), 500 (n)	op + neighbor	3	0.056	0.002	0.478	0.010	0.794	0.018
250 (c), 500 (n)	op + neighbor	4	0.711	0.051	7.342	0.181	3.657	0.089

(c) and (n) denote commercial and urban management strategies given as tolerance thresholds of ACP before spraying and interval spraying rates. Information structures include an orchard growers own property (op), expectations of future spread, and the state of their nearest neighbor's orchard. Biological parameters represent low mobility, high homing (1), high mobility, low homing (2), low mobility, low homing (3), and high mobility, high homing (4). Units of spread rate are in km/day.

Table C10. Average distance spread rate estimations (minimum and maximum bounds) for the alternate orchard configuration with a high commercial, high noncommercial threshold treatment.

Mngmt. Strategy	**Info. Structure**	**Biol. Param.**	**Maximum Spread Rate**		**Minimum Spread Rate**	
			mean	**st. error**	**mean**	**st. error**
250 (c), 500 (n)	own property	1	3.400	0.058	0.516	0.013
250 (c), 500 (n)	own property	2	4.486	0.090	0.824	0.027
250 (c), 500 (n)	own property	3	2.449	0.060	0.014	0.001
250 (c), 500 (n)	own property	4	9.856	0.191	1.841	0.095
250 (c), 500 (n)	op + expectation	1	3.307	0.041	0.470	0.012
250 (c), 500 (n)	op + expectation	2	3.404	0.058	0.801	0.021
250 (c), 500 (n)	op + expectation	3	2.458	0.056	0.011	0.001
250 (c), 500 (n)	op + expectation	4	9.995	0.213	1.738	0.075
250 (c), 500 (n)	op + neighbor	1	3.842	0.063	0.473	0.011
250 (c), 500 (n)	op + neighbor	2	4.409	0.081	0.900	0.037
250 (c), 500 (n)	op + neighbor	3	2.490	0.059	0.011	0.001
250 (c), 500 (n)	op + neighbor	4	9.821	0.192	1.598	0.065

(c) and (n) denote commercial and urban management strategies given as tolerance thresholds of ACP before spraying and interval spraying rates. Information structures include an orchard growers own property (op), expectations of future spread, and the state of their nearest neighbor's orchard. Biological parameters represent low mobility, high homing (1), high mobility, low homing (2), low mobility, low homing (3), and high mobility, high homing (4). Units of spread rate are in km/day.

Table C11. Average population front spread estimations for the alternate orchard configuration with a low interval commercial treatment.

Mngmt. Strategy	Info. Structure	Biol. Param.	Δ Radial Population Front		Δ Cardinal Directions (NSEW)	
			mean	st. error	mean	st. error
3x/yr (c), 250 (n)	own property	1	0.866	0.098	1.394	0.042
3x/yr (c), 250 (n)	own property	2	6.707	0.391	5.744	0.283
3x/yr (c), 250 (n)	own property	3	0.771	0.016	1.551	0.056
3x/yr (c), 250 (n)	own property	4	22.022	0.763	9.264	0.276
3x/yr (c), 500 (n)	own property	1	0.704	0.094	1.099	0.037
3x/yr (c), 500 (n)	own property	2	8.550	0.411	5.776	0.282
3x/yr (c), 500 (n)	own property	3	0.559	0.013	1.060	0.032
3x/yr (c), 500 (n)	own property	4	23.689	0.760	9.416	0.302

(c) and (n) denote commercial and urban management strategies given as tolerance thresholds of ACP before spraying and interval spraying rates. Information structures include an orchard growers own property (op), expectations of future spread, and the state of their nearest neighbor's orchard. Biological parameters represent low mobility, high homing (1), high mobility, low homing (2), low mobility, low homing (3), and high mobility, high homing (4). Units of spread rate are in km/day.

Table C12. Average population front spread estimations for the alternate orchard configuration with a low interval commercial treatment.

Mngmt. Strategy	Info. Structure	Biol. Param.	Δ Radial Population Front		Δ Cardinal Directions (NSEW)	
			mean	st. error	mean	st. error
12x/yr (c), 250 (n)	own property	1	1.546	0.231	1.556	0.075
12x/yr (c), 250 (n)	own property	2	7.183	0.392	6.109	0.291
12x/yr (c), 250 (n)	own property	3	0.861	0.050	1.882	0.092
12x/yr (c), 250 (n)	own property	4	22.173	0.694	10.018	0.308
12x/yr (c), 500 (n)	own property	1	1.369	0.240	1.266	0.073
12x/yr (c), 500 (n)	own property	2	7.173	0.394	5.840	0.278
12x/yr (c), 500 (n)	own property	3	0.657	0.041	1.275	0.066
12x/yr (c), 500 (n)	own property	4	23.956	0.747	9.954	0.289

(c) and (n) denote commercial and urban management strategies given as tolerance thresholds of ACP before spraying and interval spraying rates. Information structures include an orchard growers own property (op), expectations of future spread, and the state of their nearest neighbor's orchard. Biological parameters represent low mobility, high homing (1), high mobility, low homing (2), low mobility, low homing (3), and high mobility, high homing (4). Units of spread rate are in km/day.

Table C13. Average population front spread estimations for the alternate orchard configuration with a low commercial, low noncommercial threshold treatment.

Mngmt. Strategy	Info. Structure	Biol. Param.	Δ Radial Population Front		Δ Cardinal Directions (NSEW)	
			mean	st. error	mean	st. error
150 (c), 250 (n)	own property	1	0.753	0.014	1.863	0.031
150 (c), 250 (n)	own property	2	24.826	0.672	14.588	0.257
150 (c), 250 (n)	own property	3	0.774	0.015	1.362	0.052
150 (c), 250 (n)	own property	4	23.709	0.678	9.680	0.295
150 (c), 250 (n)	op + expectation	1	0.558	0.013	1.416	0.038
150 (c), 250 (n)	op + expectation	2	12.953	0.854	4.685	0.175
150 (c), 250 (n)	op + expectation	3	0.754	0.018	1.763	0.071
150 (c), 250 (n)	op + expectation	4	22.542	0.716	9.678	0.303
150 (c), 250 (n)	op + neighbor	1	0.748	0.015	1.555	0.035
150 (c), 250 (n)	op + neighbor	2	5.270	0.351	2.438	0.145
150 (c), 250 (n)	op + neighbor	3	0.770	0.016	1.484	0.062
150 (c), 250 (n)	op + neighbor	4	22.398	0.752	9.492	0.303

(c) and (n) denote commercial and urban management strategies given as tolerance thresholds of ACP before spraying and interval spraying rates. Information structures include an orchard growers own property (op), expectations of future spread, and the state of their nearest neighbor's orchard. Biological parameters represent low mobility, high homing (1), high mobility, low homing (2), low mobility, low homing (3), and high mobility, high homing (4). Units of spread rate are in km/day.

Table C14. Average population front spread estimations for the alternate orchard configuration with a low commercial, high noncommercial threshold treatment.

Mngmt. Strategy	Info. Structure	Biol. Param.	Δ Radial Population Front		Δ Cardinal Directions (NSEW)	
			mean	st. error	mean	st. error
150 (c), 500 (n)	own property	1	0.674	0.054	1.441	0.031
150 (c), 500 (n)	own property	2	6.874	0.349	5.685	0.204
150 (c), 500 (n)	own property	3	0.572	0.012	1.052	0.033
150 (c), 500 (n)	own property	4	23.210	0.796	9.478	0.295
150 (c), 500 (n)	op + expectation	1	26.342	2.052	3.785	0.265
150 (c), 500 (n)	op + expectation	2	11.581	0.473	7.342	0.395
150 (c), 500 (n)	op + expectation	3	0.575	0.014	1.125	0.038
150 (c), 500 (n)	op + expectation	4	23.414	0.814	9.303	0.285
150 (c), 500 (n)	op + neighbor	1	0.487	0.012	0.818	0.025
150 (c), 500 (n)	op + neighbor	2	7.082	0.427	5.855	0.371
150 (c), 500 (n)	op + neighbor	3	21.979	0.746	9.166	0.289
150 (c), 500 (n)	op + neighbor	4	22.940	0.717	9.747	0.277

(c) and (n) denote commercial and urban management strategies given as tolerance thresholds of ACP before spraying and interval spraying rates. Information structures include an orchard growers own property (op), expectations of future spread, and the state of their nearest neighbor's orchard. Biological parameters represent low mobility, high homing (1), high mobility, low homing (2), low mobility, low homing (3), and high mobility, high homing (4). Units of spread rate are in km/day.

Table C15. Average population front spread estimations for the alternate orchard configuration with a high commercial, high noncommercial threshold treatment.

Mngmt. Strategy	**Info. Structure**	**Biol. Param.**	**Δ Radial Population Front**		**Δ Cardinal Directions (NSEW)**	
			mean	**st. error**	**mean**	**st. error**
250 (c), 500 (n)	own property	1	0.619	0.086	1.020	0.048
250 (c), 500 (n)	own property	2	7.777	0.424	7.250	0.335
250 (c), 500 (n)	own property	3	0.565	0.013	1.091	0.037
250 (c), 500 (n)	own property	4	22.701	0.755	9.309	0.292
250 (c), 500 (n)	op + expectation	1	0.552	0.010	1.223	0.031
250 (c), 500 (n)	op + expectation	2	4.114	0.307	1.942	0.115
250 (c), 500 (n)	op + expectation	3	0.574	0.013	1.067	0.033
250 (c), 500 (n)	op + expectation	4	23.170	0.835	9.330	0.294
250 (c), 500 (n)	op + neighbor	1	0.639	0.016	0.952	0.031
250 (c), 500 (n)	op + neighbor	2	8.144	0.420	7.016	0.354
250 (c), 500 (n)	op + neighbor	3	0.566	0.013	1.035	0.031
250 (c), 500 (n)	op + neighbor	4	22.600	0.739	9.633	0.290

(c) and (n) denote commercial and urban management strategies given as tolerance thresholds of ACP before spraying and interval spraying rates. Information structures include an orchard growers own property (op), expectations of future spread, and the state of their nearest neighbor's orchard. Biological parameters represent low mobility, high homing (1), high mobility, low homing (2), low mobility, low homing (3), and high mobility, high homing (4). Units of spread rate are in km/day.

APPENDIX D

AVERAGE COUNTS OF INFESTED ORCHARDS AND MANAGEMENT:

BAKERSFIELD SPATIAL CONFIGURATION

Table D1. Average counts of infested orchards and management in the Bakersfield orchard configuration with a low interval commercial treatment.

			Commercial Orchards		Noncommercial Orchards	
Mngmt. Strategy	**Info. Structure**	**Biol. Param.**	**# Infested Orchards**	**Sprays per Orchard**	**# Infested Orchards**	**Sprays per Orchard**
3x/yr (c), 250 (n)	own property	1	11.434	6	21.372	5.239 E-4
3x/yr (c), 250 (n)	own property	2	3.269	6	5.570	0
3x/yr (c), 250 (n)	own property	3	14.816	6	17.872	1.601 E-3
3x/yr (c), 250 (n)	own property	4	1.354	6	3.844	0
3x/yr (c), 500 (n)	own property	1	4.158	6	10.888	0
3x/yr (c), 500 (n)	own property	2	3.258	6	5.548	0
3x/yr (c), 500 (n)	own property	3	2.486	6	5.500	3.368 E-4
3x/yr (c), 500 (n)	own property	4	1.428	6	3.840	0

(c) and (n) denote commercial and urban management strategies given as tolerance thresholds of ACP before spraying and interval spraying rates. Information structure includes only reacting to insect populations on their own property (own property), own property and an expectation of future spread as given by the radial spread estimator (expectations), and own property and the state of infestation on the nearest neighbor property (nearest neighbor). Biological parameters represent low mobility, high homing (1), high mobility, low homing (2), low mobility, low homing (3), and high mobility, high homing (4). Units reported are averages per simulation.

Table D2. Average counts of infested orchards and management in the Bakersfield orchard configuration with a high interval commercial treatment.

			Commercial Orchards		Noncommercial Orchards	
Mngmt. Strategy	**Info. Structure**	**Biol. Param.**	**# Infested Orchards**	**Sprays per Orchard**	**# Infested Orchards**	**Sprays per Orchard**
12x/yr (c), 250 (n)	own property	1	3.342	11	20.812	4.823 E-4
12x/yr (c), 250 (n)	own property	2	9.480 E-1	11	5.838	1.663 E-5
12x/yr (c), 250 (n)	own property	3	4.584	11	17.878	1.418 E-3
12x/yr (c), 250 (n)	own property	4	4.060 E-1	11	3.708	0
12x/yr (c), 500 (n)	own property	1	3.358	11	21.028	5.904 E-4
12x/yr (c), 500 (n)	own property	2	5.110 E-1	11	3.351	4.166 E-5
12x/yr (c), 500 (n)	own property	3	4.386	11	17.978	2.029 E-3
12x/yr (c), 500 (n)	own property	4	1.840 E-1	11	1.852	0

(c) and (n) denote commercial and urban management strategies given as tolerance thresholds of ACP before spraying and interval spraying rates. Information structure includes only reacting to insect populations on their own property (own property), own property and an expectation of future spread as given by the radial spread estimator (expectations), and own property and the state of infestation on the nearest neighbor property (nearest neighbor).   Biological parameters represent low mobility, high homing (1), high mobility, low homing (2), low mobility, low homing (3), and high mobility, high homing (4). Units reported are averages per simulation.

Table D3. Average counts of infested orchards and management in the Bakersfield orchard configuration with threshold treatments.

			Commercial Orchards		Noncommercial Orchards	
Mngmt. Strategy	**Info. Structure**	**Biol. Param.**	**# Infested Orchards**	**Sprays per Orchard**	**# Infested Orchards**	**Sprays per Orchard**
150 (c), 250 (n)	own property	1	4.182	0	6.756	0
150 (c), 250 (n)	own property	2	7.160 E -1	0	2.714	0
150 (c), 250 (n)	own property	3	5.140	0	8.466	3.992 E -4
150 (c), 250 (n)	own property	4	1	0	5	0
150 (c), 250 (n)	op + expectation	1	5.900 E -1	0.186	1.484	0
150 (c), 250 (n)	op + expectation	2	1.542	0	1.274	0
150 (c), 250 (n)	op + expectation	3	4.650	2.373 E -2	8.610	2.328 E -4
150 (c), 250 (n)	op + expectation	4	5.300 E -1	0	1.478	0

(c) and (n) denote commercial and urban management strategies given as tolerance thresholds of ACP before spraying. Information structure includes only reacting to insect populations on their own property (own property), own property and an expectation of future spread as given by the radial spread estimator (expectations), and own property and the state of infestation on the nearest neighbor property (nearest neighbor). Biological parameters represent low mobility, high homing (1), high mobility, low homing (2), low mobility, low homing (3), and high mobility, high homing (4). Units in are in km/year. Units reported are averages per simulation.

Table D4. Average counts of infested orchards and management in the Bakersfield orchard configuration with threshold treatments.

			Commercial Orchards		Noncommercial Orchards	
Mngmt. Strategy	**Info. Structure**	**Biol. Param.**	**# Infested Orchards**	**Sprays per Orchard**	**# Infested Orchards**	**Sprays per Orchard**
150 (c), 250 (n)	op + neighbor	1	3.184	0	5.992	1.663 E -5
150 (c), 250 (n)	op + neighbor	2	9.600 E -1	0	1.336	0
150 (c), 250 (n)	op + neighbor	3	4.874	0	8.442	3.992 E -4
150 (c), 250 (n)	op + neighbor	4	4.680 E -1	0	1.490	0
150 (c), 500 (n)	own property	1	2.956	0	6.930	0
150 (c), 500 (n)	own property	2	9.460 E -1	0	1.396	0
150 (c), 500 (n)	own property	3	4.648	0.028	8.532	4.033 E -4
150 (c), 500 (n)	own property	4	4.960 E -1	0	1.408	0

(c) and (n) denote commercial and urban management strategies given as tolerance thresholds of ACP before spraying. Information structure includes only reacting to insect populations on their own property (own property), own property and an expectation of future spread as given by the radial spread estimator (expectations), and own property and the state of infestation on the nearest neighbor property (nearest neighbor). Biological parameters represent low mobility, high homing (1), high mobility, low homing (2), low mobility, low homing (3), and high mobility, high homing (4). Units in are in km/year. Units reported are averages per simulation.

Table D5. Average counts of infested orchards and management in the Bakersfield orchard configuration with threshold treatments.

			Commercial Orchards		Noncommercial Orchards	
Mngmt. Strategy	**Info. Structure**	**Biol. Param.**	**# Infested Orchards**	**Sprays per Orchard**	**# Infested Orchards**	**Sprays per Orchard**
150 (c), 500 (n)	op + expectation	1	3.718	4.019 E -4	6.466	4.158 E -5
150 (c), 500 (n)	op + expectation	2	1.004	0	1.656	0
150 (c), 500 (n)	op + expectation	3	5.240	5.366 E -2	8.318	4.033 E -4
150 (c), 500 (n)	op + expectation	4	5.480 E -1	0	1.528	0
150 (c), 500 (n)	op + neighbor	1	3.740	0	5.626	0
150 (c), 500 (n)	op + neighbor	2	1.396	0	1.524	0
150 (c), 500 (n)	op + neighbor	3	4.698	0	8.266	5.198 E -4
150 (c), 500 (n)	op + neighbor	4	6.280 E -1	0	1.414	0

(c) and (n) denote commercial and urban management strategies given as tolerance thresholds of ACP before spraying. Information structure includes only reacting to insect populations on their own property (own property), own property and an expectation of future spread as given by the radial spread estimator (expectations), and own property and the state of infestation on the nearest neighbor property (nearest neighbor). Biological parameters represent low mobility, high homing (1), high mobility, low homing (2), low mobility, low homing (3), and high mobility, high homing (4). Units in are in km/year. Units reported are averages per simulation.

Table D6. Average counts of infested orchards and management in the Bakersfield orchard configuration with threshold treatments.

			Commercial Orchards		Noncommercial Orchards	
Mngmt. Strategy	**Info. Structure**	**Biol. Param.**	**# Infested Orchards**	**Sprays per Orchard**	**# Infested Orchards**	**Sprays per Orchard**
250 (c), 500 (n)	own property	1	2.826	0	8.054	8.316 E -6
250 (c), 500 (n)	own property	2	1.146	0	1.604	0
250 (c), 500 (n)	own property	3	5.168	0	8.492	3.451 E -4
250 (c), 500 (n)	own property	4	5.960 E -1	0	1.410	0
250 (c), 500 (n)	op + expectation	1	2.768	4.300 E -4	6.634	1.123 E -4
250 (c), 500 (n)	op + expectation	2	1.042	0	1.440	0
250 (c), 500 (n)	op + expectation	3	4.946	2.497 E -2	8.192	3.035 E -4
250 (c), 500 (n)	op + expectation	4	5.660 E -1	0	1.544	0

(c) and (n) denote commercial and urban management strategies given as tolerance thresholds of ACP before spraying. Information structure includes only reacting to insect populations on their own property (own property), own property and an expectation of future spread as given by the radial spread estimator (expectations), and own property and the state of infestation on the nearest neighbor property (nearest neighbor). Biological parameters represent low mobility, high homing (1), high mobility, low homing (2), low mobility, low homing (3), and high mobility, high homing (4). Units in are in km/year. Units reported are averages per simulation.

Table D7. Average counts of infested orchards and management in the Bakersfield orchard configuration with threshold treatments.

			Commercial Orchards		Noncommercial Orchards	
Mngmt. Strategy	**Info. Structure**	**Biol. Param.**	**# Infested Orchards**	**Sprays per Orchard**	**# Infested Orchards**	**Sprays per Orchard**
250 (c), 500 (n)	op + neighbor	1	3.212	0	5.462	$8.316\ E^{-6}$
250 (c), 500 (n)	op + neighbor	2	1.030	0	1.224	0
250 (c), 500 (n)	op + neighbor	3	4.688	0	8.324	$3.368\ E^{-4}$
250 (c), 500 (n)	op + neighbor	4	1.726	0	3.214	$7.900\ E^{-5}$

(c) and (n) denote commercial and urban management strategies given as tolerance thresholds of ACP before spraying. Information structure includes only reacting to insect populations on their own property (own property), own property and an expectation of future spread as given by the radial spread estimator (expectations), and own property and the state of infestation on the nearest neighbor property (nearest neighbor). Biological parameters represent low mobility, high homing (1), high mobility, low homing (2), low mobility, low homing (3), and high mobility, high homing (4). Units in are in km/year. Units reported are averages per simulation.

APPENDIX E

AVERAGE COUNTS OF INFESTED ORCHARDS AND MANAGEMENT:

ALTERNATE SPATIAL CONFIGURATION

Table E1. Average counts of infested orchards and management in the alternate orchard configuration with a low interval commercial treatment.

Mngmt. Strategy	Info. Structure	Biol. Param.	Commercial Orchards: # Infested Orchards	Commercial Orchards: Sprays per Orchard	Noncommercial Orchards: # Infested Orchards	Noncommercial Orchards: Sprays per Orchard
3x/yr (c), 250 (n)	own property	1	4.230	6	10.582	0
3x/yr (c), 250 (n)	own property	2	2.510	6	7.137	0
3x/yr (c), 250 (n)	own property	3	2.192	6	5.300	1.247 E -4
3x/yr (c), 250 (n)	own property	4	1.912	6	6.034	0
3x/yr (c), 500 (n)	own property	1	4.130	6	10.636	0
3x/yr (c), 500 (n)	own property	2	2.569	6	6.912	8.333 E -6
3x/yr (c), 500 (n)	own property	3	2.340	6	5.238	2.952 E -4
3x/yr (c), 500 (n)	own property	4	1.918	6	6.406	0

(c) and (n) denote commercial and urban management strategies given as tolerance thresholds of ACP before spraying and interval spraying rates. Information structure includes only reacting to insect populations on their own property (own property), own property and an expectation of future spread as given by the radial spread estimator (expectations), and own property and the state of infestation on the nearest neighbor property (nearest neighbor). Biological parameters represent low mobility, high homing (1), high mobility, low homing (2), low mobility, low homing (3), and high mobility, high homing (4). Units reported are averages per simulation.

Table E2. Average counts of infested orchards and management in the alternate orchard configuration with a high interval commercial treatment.

			Commercial Orchards		Noncommercial Orchards	
Mngmt. Strategy	**Info. Structure**	**Biol. Param.**	**# Infested Orchards**	**Sprays per Orchard**	**# Infested Orchards**	**Sprays per Orchard**
12x/yr (c), 250 (n)	own property	1	2.176	11	10.856	0
12x/yr (c), 250 (n)	own property	2	1.177	11	6.903	0
12x/yr (c), 250 (n)	own property	3	1.286	11	5.404	$1.247\ \text{E}^{-4}$
12x/yr (c), 250 (n)	own property	4	$6.860\ \text{E}^{-1}$	11	5.878	0
12x/yr (c), 500 (n)	own property	1	2.016	11	10.830	0
12x/yr (c), 500 (n)	own property	2	1.112	11	6.964	0
12x/yr (c), 500 (n)	own property	3	1.276	11	5.452	$2.994\ \text{E}^{-4}$
12x/yr (c), 500 (n)	own property	4	$6.546\ \text{E}^{-1}$	11	6.171	0

(c) and (n) denote commercial and urban management strategies given as tolerance thresholds of ACP before spraying and interval spraying rates. Information structure includes only reacting to insect populations on their own property (own property), own property and an expectation of future spread as given by the radial spread estimator (expectations), and own property and the state of infestation on the nearest neighbor property (nearest neighbor). Biological parameters represent low mobility, high homing (1), high mobility, low homing (2), low mobility, low homing (3), and high mobility, high homing (4). Units reported are averages per simulation.

Table E3. Average counts of infested orchards and management in the alternate orchard configuration with threshold treatments.

			Commercial Orchards		Noncommercial Orchards	
Mngmt. Strategy	**Info. Structure**	**Biol. Param.**	**# Infested Orchards**	**Sprays per Orchard**	**# Infested Orchards**	**Sprays per Orchard**
150 (c), 250 (n)	own property	1	2.964	0	12.536	0
150 (c), 250 (n)	own property	2	1.710	0	4.374	0
150 (c), 250 (n)	own property	3	2.382	0	5.630	1.996 E-4
150 (c), 250 (n)	own property	4	2.024	0	6.146	0
150 (c), 250 (n)	op + expectation	1	3.448	2.590 E-2	9.486	0
150 (c), 250 (n)	op + expectation	2	1.476	9.065 E-3	4.788	0
150 (c), 250 (n)	op + expectation	3	2.260	1.582 E-2	5.218	1.414 E-4
150 (c), 250 (n)	op + expectation	4	1.888	2.316 E-2	6.056	0

(c) and (n) denote commercial and urban management strategies given as tolerance thresholds of ACP before spraying. Information structure includes only reacting to insect populations on their own property (own property), own property and an expectation of future spread as given by the radial spread estimator (expectations), and own property and the state of infestation on the nearest neighbor property (nearest neighbor). Biological parameters represent low mobility, high homing (1), high mobility, low homing (2), low mobility, low homing (3), and high mobility, high homing (4). Units reported are averages per simulation.

Table E4. Average counts of infested orchards and management in the alternate orchard configuration with threshold treatments.

			Commercial Orchards		Noncommercial Orchards	
Mngmt. Strategy	**Info. Structure**	**Biol. Param.**	**# Infested Orchards**	**Sprays per Orchard**	**# Infested Orchards**	**Sprays per Orchard**
150 (c), 250 (n)	op + neighbor	1	2.422	0	7.246	0
150 (c), 250 (n)	op + neighbor	2	2.278	0	5.548	0
150 (c), 250 (n)	op + neighbor	3	2.430	$1.495\,E^{-4}$	5.522	$8.316\,E^{-5}$
150 (c), 250 (n)	op + neighbor	4	1.974	0	6.184	0
150 (c), 500 (n)	own property	1	3.540	0	1.032	0
150 (c), 500 (n)	own property	2	1.564	0	4.676	0
150 (c), 500 (n)	own property	3	2.334	0	5.310	$3.326\,E^{-4}$
150 (c), 500 (n)	own property	4	1.978	0	6.512	0

(c) and (n) denote commercial and urban management strategies given as tolerance thresholds of ACP before spraying. Information structure includes only reacting to insect populations on their own property (own property), own property and an expectation of future spread as given by the radial spread estimator (expectations), and own property and the state of infestation on the nearest neighbor property (nearest neighbor). Biological parameters represent low mobility, high homing (1), high mobility, low homing (2), low mobility, low homing (3), and high mobility, high homing (4). Units reported are averages per simulation.

Table E5. Average counts of infested orchards and management in the alternate orchard configuration with threshold treatments.

			Commercial Orchards		Noncommercial Orchards	
Mngmt. Strategy	**Info. Structure**	**Biol. Param.**	**# Infested Orchards**	**Sprays per Orchard**	**# Infested Orchards**	**Sprays per Orchard**
150 (c), 500 (n)	op + expectation	1	3.272	3.238 E-2	6.876	0
150 (c), 500 (n)	op + expectation	2	2.258	1.413 E-2	5.570	0
150 (c), 500 (n)	op + expectation	3	2.298	2.291 E-2	5.266	1.705 E-4
150 (c), 500 (n)	op + expectation	4	1.846	4.610 E-2	6.320	0
150 (c), 500 (n)	op + neighbor	1	3.510	0	8.852	0
150 (c), 500 (n)	op + neighbor	2	2.142	0	6.350	0
150 (c), 500 (n)	op + neighbor	3	2.038	0	6.312	8.316 E-6
150 (c), 500 (n)	op + neighbor	4	1.806	0	6.068	0

(c) and (n) denote commercial and urban management strategies given as tolerance thresholds of ACP before spraying. Information structure includes only reacting to insect populations on their own property (own property), own property and an expectation of future spread as given by the radial spread estimator (expectations), and own property and the state of infestation on the nearest neighbor property (nearest neighbor). Biological parameters represent low mobility, high homing (1), high mobility, low homing (2), low mobility, low homing (3), and high mobility, high homing (4). Units reported are averages per simulation.

Table E6. Average counts of infested orchards and management in the alternate orchard configuration with threshold treatments.

			Commercial Orchards		Noncommercial Orchards	
Mngmt. Strategy	**Info. Structure**	**Biol. Param.**	**# Infested Orchards**	**Sprays per Orchard**	**# Infested Orchards**	**Sprays per Orchard**
250 (c), 500 (n)	own property	1	3.378	0	9.496	0
250 (c), 500 (n)	own property	2	3.224	0	9.206	0
250 (c), 500 (n)	own property	3	2.330	7.477 E -5	5.492	2.703 E -4
250 (c), 500 (n)	own property	4	1.998	0	6.488	0
250 (c), 500 (n)	op + expectation	1	3.376	2.189 E -2	8.482	0
250 (c), 500 (n)	op + expectation	2	2.484	3.836 E -2	6.668	0
250 (c), 500 (n)	op + expectation	3	2.402	2.419 E -2	5.546	3.243 E -4
250 (c), 500 (n)	op + expectation	4	1.930	4.283 E -2	6.222	0

(c) and (n) denote commercial and urban management strategies given as tolerance thresholds of ACP before spraying. Information structure includes only reacting to insect populations on their own property (own property), own property and an expectation of future spread as given by the radial spread estimator (expectations), and own property and the state of infestation on the nearest neighbor property (nearest neighbor). Biological parameters represent low mobility, high homing (1), high mobility, low homing (2), low mobility, low homing (3), and high mobility, high homing (4). Units reported are averages per simulation.

Table E7. Average counts of infested orchards and management in the alternate orchard configuration with threshold treatments.

			Commercial Orchards		Noncommercial Orchards	
Mngmt. Strategy	**Info. Structure**	**Biol. Param.**	**# Infested Orchards**	**Sprays per Orchard**	**# Infested Orchards**	**Sprays per Orchard**
250 (c), 500 (n)	op + neighbor	1	3.960	0	1.055	0
250 (c), 500 (n)	op + neighbor	2	3.084	0	7.574	0
250 (c), 500 (n)	op + neighbor	3	2.246	3.364 E -4	5.504	3.119 E -4
250 (c), 500 (n)	op + neighbor	4	1.818	0	6.074	0

(c) and (n) denote commercial and urban management strategies given as tolerance thresholds of ACP before spraying. Information structure includes only reacting to insect populations on their own property (own property), own property and an expectation of future spread as given by the radial spread estimator (expectations), and own property and the state of infestation on the nearest neighbor property (nearest neighbor). Biological parameters represent low mobility, high homing (1), high mobility, low homing (2), low mobility, low homing (3), and high mobility, high homing (4). Units reported are averages per simulation.