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Modeling the Effect of Spatial Externalities on Invasive Species Management

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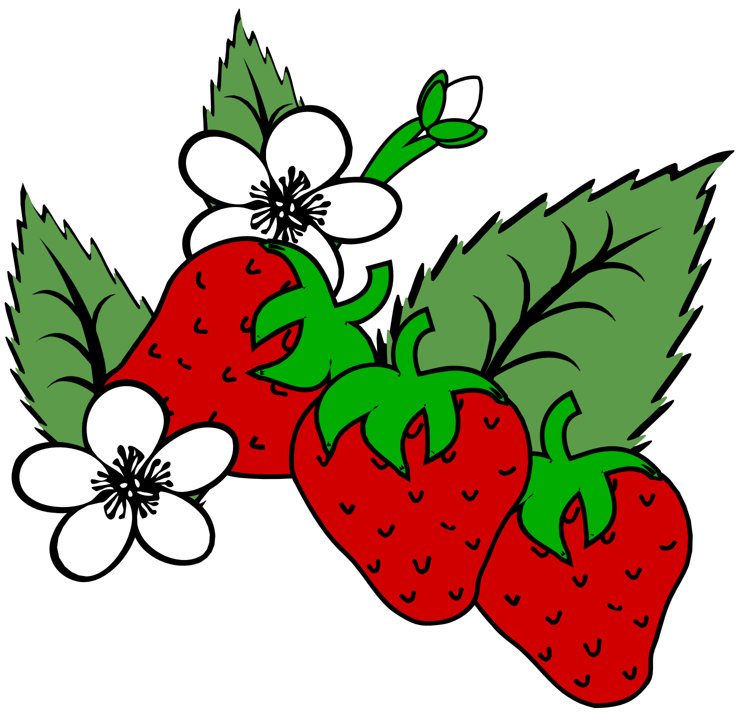

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Abstract

Changes in production conditions associated with biological invasions can be complex. As a result, modeling invasive species management decisions can be difficult. Modeling these decisions is further compounded by externalities associated with spatial relationships among growers. In order to calculate optimal management decisions, an accurate bioeconomic model of the feedback between grower decisions and the new biological interactions created by an invasive species population is needed. In this paper, a bioeconomic model is used to explicitly analyze how externalities caused by spatial relationships among agricultural producers affect optimal invasive species management decisions. The example of the coordinated greenhouse whitefly management in the Oxnard, CA, area is discussed. This is an interesting example because of the complex cycle of host crops used by the whitefly and the effect this cycle has on the optimal whitefly management decisions for strawberry growers.

Three research objectives achieved in this paper include first, using the model to assess how the spatial relationship among growers affects incentives for regional invasive pest management. Second, analyze whether current policies could be adjusted to substitute for coordination among growers. Third, the use of the bioeconomic model to identify factors for this specific case that affect whether or not growers may voluntarily coordinate their management decisions.

I find that spatial relationships among growers affect the need for coordination in the strawberry/whitefly case. Whitefly migrations across host crop fields require growers to manage the whitefly on a regional basis in order to maximize strawberry producer welfare. The results also indicate that the amount of effort needed to achieve coordination required is limited; the only requirement is that information related to field management be shared among growers of whitefly host crops. The results from the bioeconomic model describe the biological and economic feedback of the grower's decision which allows policymakers to identify the willingness of producers to coordinate at various times of year. In the Oxnard strawberry/whitefly case, for example, growers will not find it optimal to adjust their application timing for a second immigration of adult greenhouse whiteflies when they occur near the end of the season, such as in May or June, but will for earlier points in the season.

Three policy implications of the results from the strawberry/whitefly case are also discussed in the paper. First, adjustments to current policies regulating whitefly management do not remove the need for coordination among growers to them. Also, it was found that current policies do not, by themselves, generate the need for coordination. Finally, the results show it is not always necessary to create a central agency for regional invasive species management.

Key Words: Invasive species, strawberry, greenhouse whitefly, externality, optimal management.

Modeling the Effect of Spatial Externalities on Invasive Species Management

Gregory J. McKee*

1 Introduction

Changes in production conditions caused by biological invasions can be complex. As a result, modeling invasive species management decisions can be difficult. Externalities associated with spatial relationships among growers compound this difficulty. In order to create the optimal policy for invasive species management, one must consider the effects of management decisions made by a grower in one field on the decisions of growers managing adjacent fields. Bioeconomic models can suggest policies that should be developed by projecting their impacts through grower's profits under many responses to regulatory alternatives, given economic and biological constraints.

In this study, I develop a bioeconomic model to analyze how externalities caused the migration of invaders among adjacent host crop fields affect optimal invasive species management decisions and to suggest the potential design of optimal management policies for a region. To that end, I examine how pest management decisions in one host crop field affect profits from another host crop in an adjacent field and whether a given set of regulations result in responses that favor increased profits.

In this study, the planting and harvesting decisions of a grower of alternative host crops affect the management decisions of fall-planted strawberry growers in adjacent fields by influencing the time adult greenhouse whiteflies migrate into them. The externalities from this movement suggest that managing the whitefly on a regional basis will increase strawberry producer welfare relative to the outcome that would result from growers making these decisions independently. The analysis conducted in this study confirms this intuition: profits from regional greenhouse whitefly population management can exceed those from private, single-field level management. In such cases, obtaining these higher profits will require growers to coordinate their efforts. However, in this case, I find that the amount of coordination required is limited and unlikely to be very costly; the only requirement is that information regarding field management be shared among growers of whitefly host crops, as detailed below.

This report proceeds as follows. First, I describe features of the strawberry/whitefly interaction for fall-planted strawberry growers in the Oxnard area, and the methods growers of many host crops adopted to reduce the size of the regional whitefly population between 2002 and 2003.[1] Second, I develop a bioeconomic model to calculate whether management decisions of a grower in one field affect the optimal management decisions of a host crop grower in an adjacent fall-planted strawberry field. Third, I use the model to measure whether coordinated whitefly

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[1] Although I focus on the Oxnard area, qualitatively similar results occur between growers in the Watsonville, CA area when a fall-planted field is located adjacent to a field that has been in place for more than one season, which occurs in approximately 8% of statewide acreage (California Strawberry Commission, 2004).

management among growers of various host crops in the Oxnard area would increase profits from fall-planted strawberry production. Finally, I use these results to determine what type of coordination policies could be used by fall-planted strawberry growers and their neighbors to increase the welfare of the strawberry growers.

2 Background

2.1 The Market for Strawberries in California

Strawberries are grown commercially in five geographically distinct regions along the California coast. From south to north, these are the San Diego area, Orange County, the Oxnard plains in Ventura County, the Santa Maria Valley, and the Watsonville/Salinas area. The proximity of these areas to the coast creates an ideal climate for strawberry production and favorable habitat for the greenhouse whitefly.

The market price for fresh strawberries within and across growing regions varies over the course of the year. During the period when there are fewer strawberries harvested (between October and January), a pound of fresh strawberries has historically sold at wholesale for more than $1.00 and occasionally more than $2.00 (USDA-AMS). During the middle of the year, between March and September, the fresh wholesale price is typically around $0.50 per pound.[2]

This cycle of high prices in the fresh market at the beginning and end of the year and low prices mid-year is driven by several factors. First, fresh strawberries are highly perishable. Since they cannot be stored, the current price represents demand and harvest conditions at the time. Second, yields from any given field start small (a few hundred grams/plant of fruit each month), peak (exceeding 1 kilogram/plant of fruit each month), and then decline. A third reason for lower prices in the middle of the season is the increased availability of substitute fruits such as grapes and cherries. Fourth, as the year progresses southern growing regions are steadily harvesting and northern regions are coming into full production. This increases the supply of fresh strawberries relative to early in the year. This cycle is an important temporal element to consider when identifying an optimal whitefly management strategy, because the value of the crop—and hence, incentives for pest control—changes from month to month.

To take advantage of the relatively higher wholesale prices for fresh strawberries at the beginning and end of the year, strawberry growers in the Oxnard area have altered their cropping cycles to include a summer planting. Yields are harvested primarily between September and December, unlike the bulk of the traditional fall plantings, which are harvested statewide between February and September. Statewide, summer-planted acreage expanded by 188% between 1998 and 2004, increasing from 1,208 to 3,480 acres, or from about 5% to 11% of statewide acreage (California Strawberry Commission, 2005). The addition of a summer strawberry crop, and perhaps, as some experts suggest, genetic changes in the greenhouse whitefly, have contributed to whitefly infestations in these regions.

[2] These averages are based on sales data between 1988 and 2003.

2.2 The Greenhouse Whitefly: *Trialeurodes vaporariorum*

The whitefly is common to the coastal region, but had not previously used strawberries as a host. Hence, it might be termed a "resident invader" of strawberries. The largest field populations observed after this invasion were in the Oxnard growing region in 2000–01. Smaller outbreaks occurred in the 2001–2002 and 2002-2003 seasons. The addition of a summer strawberry crop and perhaps, as some experts suggest, genetic changes in the greenhouse whitefly contributed to whitefly infestations in the region.

The greenhouse whitefly damages strawberry plants by feeding on the nutrients in the plants' sap, which results in yield losses (Byrne, Bellows, and Parrella, 1990). Entomologists have conducted field analyses to measure the yield loss. Losses in affected fields range from 20%-25% in the Oxnard area (California Strawberry Commission, 2003).

2.3 Chemical Control of the Greenhouse Whitefly

Cultural and biological control techniques alone have not been effective against outdoor infestations of the greenhouse whitefly in strawberries (Toscano and Zalom, 2003; Phillips, Rodgers, and Malone, 1999). Chemical pesticides, therefore, are an important part of an effective whitefly control program. Since the greenhouse whitefly reproduces rapidly and tends to live on the underside of leaves, it is a difficult pest to manage effectively with chemicals. Heavy use of older pesticides, such as organophosphates, on greenhouse whitefly populations on other crops, including greenhouse and ornamental plants, has fostered their resistance to those chemicals. This has increased the need for and value of innovations in chemical control.

A new chemical registered in 2003, pyriproxyfen, marketed by the Valent Corporation as Esteem, is relatively effective against whiteflies on strawberries. Pyriproxyfen, an insect growth regulator, works principally by killing the eggs and nymph whiteflies on the strawberry plant; it has a limited direct effect on the adults (Ishaaya, DeCock, and Degheele, 1994). Field observations of pyriproxyfen used on strawberries indicate that a single application reduces the adult and juvenile populations for between one month to nine weeks (Bi, Toscano, and Ballmer, 2002b,c).

Resistance to pyriproxyfen has been observed in other species of whitefly. Specifically, Bemisia tabaci in Europe, and Israel has shown resistance to pesticides that use pyriproxyfen as the active ingredient. Although recorded incidences of resistance to this and other chemicals appear to be increasing (Denholm and Horowitz, 2000), there is no evidence of development of significant resistance to pyriproxyfen by the greenhouse whitefly in California. The number of pyriproxyfen applications is restricted by use regulations created by the California Department of Pesticide Regulation. This is designed to delay the development of greenhouse whitefly resistance to pyriproxyfen. Similar use restrictions exist for pyriproxyfen and other active ingredients in pesticides applied to other crops, [3] so analyzing the impact of these restrictions on management of invasive species in agriculture is useful when resistance management is a policy objective.

[3] The EPA label for pyriproxyfen lists several crops for which applications are limited to once or twice a year (Crop Data Management Systems, various years).

3 A Bioeconomic Model of Growers' Invasive Pest Management Decisions

To understand how economic agents might act in order to manage a biological invasion while constrained by the biology of the system and regulations, I must implement a decision-making model. In this section, I develop a model of whitefly population development and combine it with a simple model of grower behavior for managing a greenhouse whitefly invasion at the single-field level. I then modify it to account for the effect of management activities in adjacent fields.

Better understanding of the rate of strawberry yield loss requires an understanding of the fly's physical development. Many organisms, including the greenhouse whitefly, cannot regulate their internal temperature. The rate of physical development depends on the amount of heat in the environment. Phenology[4] models predict the timing of the whitefly's physical development.[5] These models describe the total amount of heat the whitefly must be exposed to in order to mature. Each degree of heat during a 24-hour period, above a minimum temperature that must be met for development to occur, is called a degree-day (°D). Table 1 lists the cumulative amount of environmental heat, measured in degree-days (°D), needed to reach each stage in the whitefly life cycle.[6]

Table 1. Development Time in Cumulative Degree-days (°D) for the Greenhouse Whitefly, in Degrees Fahrenheit

Life Stage	Development Time (°D)
Egg	221.2
Nymph	464.0
Egg to Adult	685.3

Source: Osborne (1982)

The physiological development of the greenhouse whitefly consists of a series of life stages (Byrne and Bellows, 1991; Byrne, Bellows, Parrella, 1990). The first stage is as an egg. The second through fifth stages are called instars, which is defined as a stage in the life of an arthropod (such as the greenhouse whitefly) between each molt (the process of shedding the exoskeleton). The final stage is as an adult. With the exception of eggs, whiteflies at all of these stages cause damage to strawberry plants through feeding on plant nutrients; no damage occurs at the egg stage. Each stage is accompanied by a natural rate of mortality.

[4] Phenology is the study of the timing of recurring biological phases.

[5] See ucipm.ucdavis.edu/weather/ddphenology.html for a more complete discussion of phenology models.

[6] To validate Osborne's development times, I compare them with the results of an alternative model suggested by Hulspas-Jordaan and van Lenteren (1989). These authors estimated a series of quadratic equations that regress development time for each stage of the whitefly life cycle on daily temperature, based on data obtained in controlled experiments. I compare the development times from both models during parts of the year in Watsonville when the thermal threshold was exceeded (late May – early October 2003). The development times estimated by the two models for this period are comparable.

An adult female whitefly can lay hundreds of eggs during its lifetime and can lay zero to about fifteen per day, depending on temperature. This process is called oviposition. Because the rate of physiological development depends on the amount of heat available, the amount of time it takes for an egg to hatch depends on the time of year. In the Oxnard area, eggs hatch within 19 to 20 days if laid in early January, or in as little as 6 or 7 days in the mid- and late summer months.

The four instar stages differ from each other only in the size of the growing nymph and are collectively referred to as the nymph part of the life cycle. In the Oxnard area, the nymph stages range from 35 to 38 days for eggs laid in early to mid-January to as little as 14 to 15 days for eggs laid in early July through mid-August. At the close of the nymph stage, the mature adult whitefly emerges, now with wings, allowing it to fly from one location to another. Observations and anecdotal evidence from the Oxnard area in 2000 and 2001 indicate that the adult whitefly population in fall-planted strawberries peaks in November, February, and April (Bi, Toscano, and Ballmer, 2002a). Short generation times, especially during warmer periods of the year, result in multiple generations of greenhouse whiteflies being present on the leaves simultaneously. As a result, whitefly populations can develop rapidly in commercial strawberry fields.

When a grower understands the relationship between temperature and whitefly physical development, he can make better-informed decisions about when to apply chemical pesticides to maximize profits than when these decisions are made based on market conditions alone. To model the development of greenhouse whitefly populations, I created a parameterized model of the development of a greenhouse whitefly population on a typical strawberry plant leaf. The selection of parameters affecting the rate of whitefly population development was influenced by the work of Hulspas-Jordaan and van Lenteren (1989), who modeled the population dynamics of the greenhouse whitefly on tomatoes in controlled conditions. Parameters include oviposition and mortality rates for each life stage, plant carrying capacity, and the relationship between mortality rates and weather and plant nutrient levels. The data used to estimate the parameter values in this model were collected on a common strawberry variety, Camarosa, near Oxnard, CA. In the 2003-4 growing season, this represented at least 31% of statewide planted acreage and was the most common commercial variety at the time.[7] This model should, therefore, be considered as a representative case for greenhouse whitefly infestations of strawberries.

The main function of this model is to simulate the timing and size of whitefly population peaks by replicating the observed life cycle of the greenhouse whitefly in a commercial strawberry field. The model uses the degree-days listed in Table 1 to estimate whitefly physiological development; using these values I can model the length of time any cohort of whiteflies is at the egg or nymph stage. Once the fly's physical development rate is known, the sizes of the daily whitefly egg, nymph, and adult cohorts are adjusted over time by assigning values for greenhouse whitefly oviposition and mortality rates, the life span of adult whiteflies, and pesticide efficacy. Values for these parameters are selected such that the timing of the

[7] In 2004, 31.1% of statewide acreage (9,832 of 31,639) was planted with Camarosa, the most common short-day variety. Ventana is the second most popular at 8.8% of statewide acreage (2,777). Various proprietary varieties represented 30.8% of the statewide total acreage in 2004 (9,756) (California Strawberry Commission, 2004).

simulated flow of eggs, nymphs, and adults through time replicates the observations at each sample date. The parameter values are comparable to greenhouse whitefly reproduction, mortality, and pesticide efficacy rates published in the entomological literature (Bi, Toscano, and Balmer, 2000b,c; Hulspas-Jordaan and van Lenteren, 1989).

The model is also used to simulate the effect of pyriproxyfen on the whitefly population. The effect of alternative pyriproxyfen application dates on whitefly population development is assessed by mathematically representing their effect in the model, with the parameter value estimated from the same field data used to estimate the previous parameters. All three populations are modeled because pyriproxyfen affects each population differently. Therefore, the effect of alternative application dates has to be assessed on the simultaneous development of the egg, nymph, and adult populations.

I make several assumptions to simplify the behavioral part of the model. First, I assume that the grower maximizes profits from a representative field infested with greenhouse whiteflies at planting. I assume that there are constant returns to scale and analyze returns for each treatment scenario on a per-acre basis. I scale up the biological model from the plant level to the acre level, and I assume the field is uniformly infested with whiteflies. Finally, although yields and harvest costs are directly influenced by the use of pesticides, because the number of higher-quality berries harvested per unit of time increases when they are applied, I ignore this effect due to a lack of data.

The grower chooses the timing of pyriproxyfen treatments to maximize:

$$\sum_{t=1}^{T}\pi_t = \sum_{t=1}^{T}(p_t)Y_t\left(WF_t\left(\sum_{k=1}^{t}E_{i,k}\right)\right) - C_e - C_{\bar{e}}\ ,\ t\in[1,T] \qquad (1)$$

$$\text{subject to } 0 \le \mathrm{Y_t}\left(\mathrm{WF_t}\left(\sum_{k=1}^{t}\mathrm{E_{i,k}}\right)\right) \le g\ ,\ i \in \{0,1,2\},\ t\in[1,T] \qquad (2)$$

$$0 \le \sum_{t=1}^{T}\mathrm{E_{i,t}} \le 2, \forall\, t \qquad (3)$$

$$WF_t \ge 0, \forall\, t \qquad (4)$$

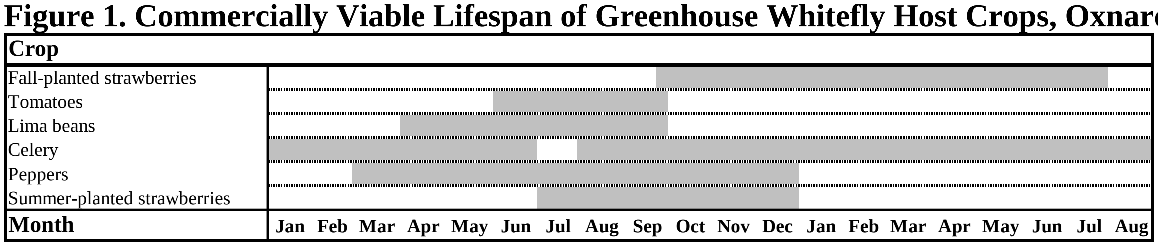
where π_t refers to profits net of treatment and other expenses in week *t*, *T* is the last week the plants remain in the ground, and p_t is the weighted average weekly regional wholesale fresh and processed strawberry price. The total number and the timing of pyriproxyfen treatments in week *t* is expressed in $\mathrm{E_{i,t}}$, which is the i^{th} pyriproxyfen application in the season in week *t* at the label rate and $\sum_{k=1}^{t}E_{i,t}$ is the cumulative number of applications within week *t*. Finally, C_e is the per-acre cost of pyriproxyfen and $C_{\bar{e}}$ refers to other all expenses in week *t*, which are assumed to be unaffected by the application of pyriproxyfen. The model constraints are the following: the weekly yield of the infested field cannot exceed that of a field that is not infested, *g* (Eq. 2);[8] at most, two pyriproxyfen applications can be made on the same acre per season (Eq. 3); and the number of whitefly-days[9] can never be negative (Eq. 4). Equations (2) and (4) represent the biological features of the model. Equation (3) represents the constraints imposed by the restrictions on pyriproxyfen use.

The single-field whitefly management model uses the parametric simulation of the number of whitefly-days for any week *t*, the strawberry yield for any week *t* as a function of the number of whiteflies, and the regulatory constraints selected for analysis. The model is evaluated by deriving the optimal treatment date for one or more pyriproxyfen treatments by finding the week in which maximum profits are obtained from the strawberry yield. At the optimum, profits from strawberry production, when the field is infested by greenhouse whiteflies, are $\sum_{t=1}^{T}\pi_t^* = \sum_{t=1}^{T}(p_t)Y_t\left(WF_t\left(\sum_{k=1}^{t}E_{i^*,k^*}\right)\right) - C_e - C_{\bar{e}}$ where the number, *i*, and timing, *k*, of pyriproxyfen treatments maximize profits.[10]

4 The Effect of Spatial Relationships among Oxnard Area Growers on Regional Greenhouse Whitefly Population Development

The greenhouse whitefly population in the Oxnard area moves through an annual cycle of host crops. Many crops grown in the area are viable greenhouse whitefly hosts, including tomatoes, lima beans, bell peppers, celery, and summer and winter strawberry plantings. Host crops are often in adjacent fields, well within the flight range of an adult whitefly. The commercial duration of these crops is displayed in Figure 1. As Figure 1 shows, many host crops are in the ground simultaneously.

Figure 1. Commercially Viable Lifespan of Greenhouse Whitefly Host Crops, Oxnard, CA



[8] Equation (2) was estimated using yield data collected from the same field experiment used to estimate the parameter values described above. A negative and statistically significant relationship between strawberry yields and the size of the whitefly population and the amount of time it had been developing on the plant. The statistical analysis has been omitted due to constraints on the length of the paper. It is available upon request.

[9] To calculate the number of whitefly-days, let A_t represent the number of adult whiteflies observed on a leaf on the sample date *t* and let *n* equal the number of weeks between samples. Then the average number of whitefly-days in any period of *n* weeks between two observations is estimated by the following equation: $WF_t = [n] \times [7/2] \times [A_t + A_{t-n}]$, $n=1, \ldots, 52$.

[10] The required dosage is fixed. The amount of chemical applied per acre is not a choice variable.

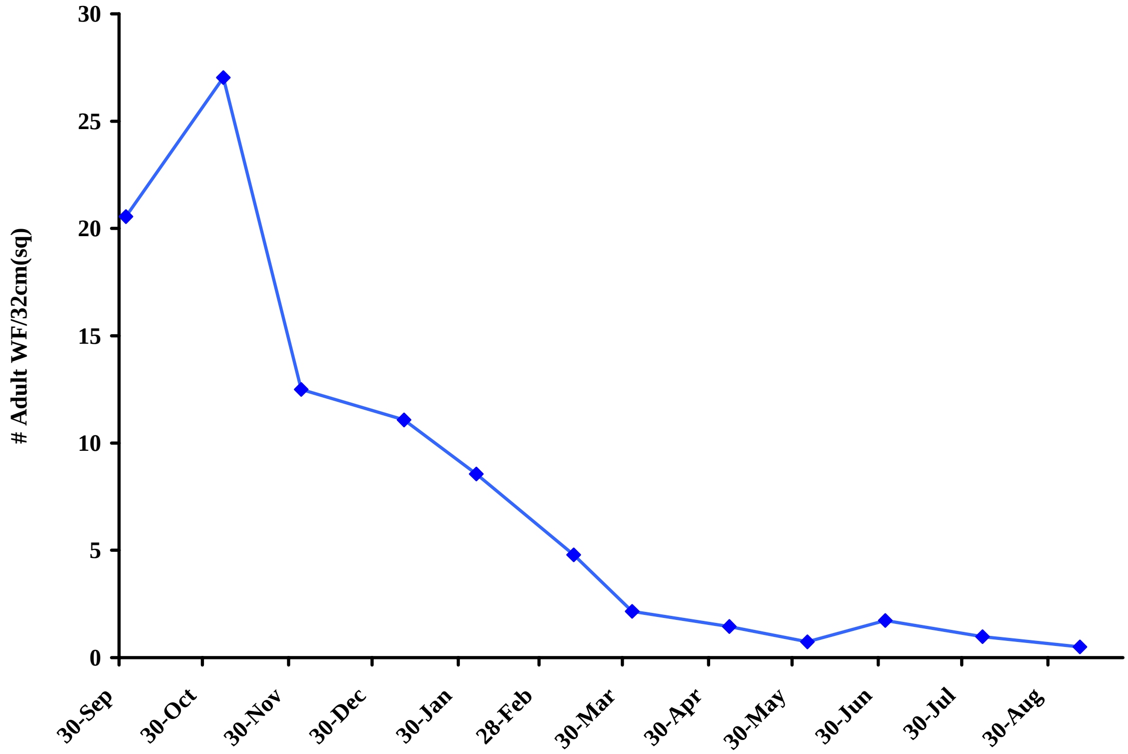
Although adult greenhouse whiteflies tend to remain on or near the host plant on which they were born (Benchwick, 2005; Ishida, 2005; Byrne, Bellows, and Parella, 1990), the entomological literature indicates that when the plant is removed, the adult whitefly population will migrate to nearby hosts, including commercially grown host crops (weeds, especially Malva) or even a bare field (Byrne, Bellows, and Parella, 1990). This factor is significant for the Oxnard area since many viable host crops are in the ground simultaneously, but are removed at different times.

The observations of Bi, Toscano, and Ballmer (2002a) and Zalom (2004) indicate a sequence of whitefly hosts. They sampled the number of adult whiteflies per leaf on a sequence of four host crops in the Oxnard area, during a ten-month period between 2000 and 2001. These data show that since lima beans and tomatoes are growing vigorously at the time fall-planted strawberries are removed (in July), they become the preferred greenhouse whitefly hosts after fall-planted strawberries. Between July and September, summer strawberry plantings are in the ground simultaneously with lima beans and tomatoes and become the preferred greenhouse whitefly host plant after they are removed. Finally, fall-planted strawberries again become the preferred host by January, when summer plantings are removed.

Because of the economic loss suffered due to the greenhouse whitefly, growers in the Oxnard area adopted the objective of controlling the development of the whitefly population through coordinated regional management. Many stakeholders participated in voluntary efforts to promote the regional management of the whitefly population in the Oxnard area, including growers of viable host crops such as strawberries and lima beans; the Ventura County Agricultural Commissioner; pest control advisors; and University of California scientists. Representatives from these groups formed a team called the Whitefly Action Committee. The committee's goals were to document the timing and size of whitefly migrations within the area, promote research on effective whitefly control, and develop a regional whitefly reduction strategy that all growers could follow.

In order to assess the progress of its whitefly reduction strategy and to coordinate the grower's management efforts, the Whitefly Action Committee collected and distributed data about the size and timing of adult greenhouse whitefly population migrations between alternative host crop fields. I used these data to calculate a single monthly average adult whitefly migration rate so any general trend in the size of the adult whitefly population movement could be observed during the period the committee was active. These averages are shown in Figure 2. These data show that an overall decline in the rate of adult whitefly migration was observed between September 2002 and August 2003. It is reasonable to assume that the decline in adult whitefly migration rates is related to declining field populations of greenhouse whiteflies, especially since it is supported by anecdotal reports. No migrations as large as those observed during the 2002-2003 growing season have occurred since that time.

Figure 2. Average Adult Greenhouse Whitefly per 32cm²/24 Hour Period, Oxnard, CA, October 2002 - September 2003



I interviewed each member of the Whitefly Action Committee and asked what conditions they hypothesized led to the decline in the size of adult whitefly migrations, and thus the regional whitefly population, during the 2002-2003 season. The consensus of these seven interviewees was that a combination of factors was at work. Members of the committee hypothesized that one factor contributing to the decline in adult whitefly migration was the use of foliar applications of pyriproxyfen. A second factor was changes in field management practices, especially the timely removal of old or abandoned host plants. A third factor suggested by some members of the committee was the perception that a cooler winter in 2002-2003, relative to the previous two or three years, slowed the rate of whitefly population development.

The final factor the interviewees cited was coordinated whitefly population management among growers. All of them agreed with the statement that the combination of communicating a specific whitefly management strategy for affected crops in the area (including making timely pesticide applications, diligently removing abandoned host plant material) and making public reports about the monthly aggregated whitefly population data through the communication network created by the Whitefly Action Committee, led to a more rapid decline in the whitefly population than would have occurred without this network. The members of the committee explained that these data were the only source of information for growers and PCAs regarding the regional nature of adult whitefly movement, the reduction in the volume of whitefly migration, and the relationship between whitefly movement timing and host crops in the area.

The members of the committee indicated that they believed whitefly management decisions made by isolated individual growers would not have led to such a rapid decline in the whitefly migration levels as was observed.

This belief was based on two perceptions. First, committee members believed that individual growers used the information regarding the size and timing of whitefly population movements they collected and distributed by the committee to make different whitefly management decisions then they would have made without it.[11] Second, committee members believed that the changes growers made in management practices as a result of being provided with this information, led to a greater decrease in whitefly migration than would have occurred under the management practices growers would have used if the committee had not distributed the information.[12] Both of these perceptions suggest that the most effective way to manage a pest, whose population builds as it moves through a continuous cycle of host crops, may be through regional coordination. The bioeconomic model will be used in the next section to assess the benefits of coordination to strawberry growers.

4.1 Economic Analysis of the Externalities of Pest Management

Since the externalities of field management practices affect the whitefly management decisions of fall-planted strawberry growers, in this section the bioeconomic model will be used to determine whether coordination among growers in the Oxnard area could increase profits from production of fall-planted strawberries. For this analysis, I assume that an adjacent host crop field is infested with whiteflies and that the timing of whitefly migrations is driven by the removal of a host crop in an adjacent field; if the adjacent field has no whiteflies, no migration is assumed to occur. For example, if a fall planting of strawberries has recently been made and the plants in an adjacent, infested field are removed, then the adult whiteflies in that adjacent field will be displaced and will migrate to the strawberry field. For purposes of this analysis, immigration is defined as an increase in the number of adult whiteflies per leaf on all plants in the fall-planted strawberry field as a result of their arrival from a source other than the observed field, and not the natural increase in the adult whitefly population associated with the reproduction of the whiteflies which entered the field at planting.

To determine the optimal timing for a one-treatment control program, I used the numerical simulation model of the greenhouse whitefly population to compute the effect of a single application of pyriproxyfen on the whitefly population and profit for every week in the season. The size of the whitefly population affects total strawberry yields through the amount of

[11] This perception could be tested using survey techniques; however, doing so was beyond the scope of this report. The interviews of fall-planted strawberry growers for this study indicated that the information provided by the committee was essential for their decisions about whether or not to treat their field with imidacloprid and pyriproxyfen. In fact, one grower indicated that without that information, he would "still be guessing" about how to make whitefly management decisions.

[12] There is no rigorous way to test the second hypothesis–the control cannot be constructed without undue risk of whitefly infestation to growers in the area. It appears that stakeholders used the strategy and data provided by the committee to observe whether or not coordinated management decisions had any effect on the regional whitefly population. The subsequent whitefly population movement data suggest that the decline in the size of the whitefly population was related to these decisions.

damage it causes to the plant. Profit, therefore, is determined by the magnitude and timing of the strawberry yield increase resulting from an application of pyriproxyfen, which reduces the whitefly population. I identified the optimal timing of the application by combining results of the population, yield, and economic model to determine the week when the estimated return to the simulated pyriproxyfen application is greatest.

To determine the effect of these spatial relationships among producers on optimal greenhouse whitefly management in fall-planted strawberry fields, I will compare the timing for pyriproxyfen applications for a strawberry grower who only considers the effect of a whitefly infestation at planting with the optimal timing for a grower who also considers a second infestation later in the season associated with an immigrating adult whitefly population from another host crop. If the timing of the pyriproxyfen applications does not change as a result of considering the second infestation, then the strawberry grower's private whitefly control decision is optimal and unaffected by spatial relationships among growers. Alternatively, if the timing of the pyriproxyfen applications does change as a result of the second infestation, then coordination among growers may be needed in order to maximize returns from whitefly management.

I will also assess whether the pyriproxyfen use restrictions themselves affect the need for the coordination of whitefly control activities among growers. It could be, for example, that relaxing the constraint in Equation (3) to allow a third pyriproxyfen application could substitute for coordination. This would be the case if making a third pyriproxyfen application would eliminate the need for growers to adjust the timing of pyriproxyfen applications based on the timing of migrations in order to increase profits.

Finally, in this analysis, I do not explicitly consider the effect of strawberry grower decisions on neighboring growers, because data do not exist about the relationship between greenhouse whitefly population dynamics and yield losses for alternative host crops.

4.1.1 Two Pyriproxyfen Applications

In this subsection, I assess the effect of a second adult whitefly immigration on the optimal timing of two pyriproxyfen applications on fall-planted strawberries in the Oxnard area. In each of these cases, I calculate the optimal timing of two applications of pyriproxyfen, given an infestation of adult whiteflies at planting, followed by a second immigration of adult whiteflies at various points in the strawberry growing season, which represents the effect of decisions made by growers of other host crops. To ascertain the effect of a second immigration on optimal pyriproxyfen application timing at any point in the season, I consider twelve different possible weeks for a second infestation. I then compare the optimal pyriproxyfen treatment dates with those calculated in the absence of a second immigration.

The results of this analysis show that multiple whitefly immigrations may make it optimal to change the timing of an pyriproxyfen application. The level of coordination required in order for growers of fall-planted strawberries to realize this, changes over the course of the season. First, there are points during the strawberry growing season when the only way for a strawberry grower to optimally time his pyriproxyfen applications is for him to receive information from adjacent growers about intended host plant removal times. In these cases, the grower would find it optimal to change at least one pyriproxyfen application date relative to when a second immigration is not considered and would need to make this decision before he could observe the host plant removed; in other words, for this analysis, coordination is required when a grower would find it optimal to adjust an application time to a week prior to the host crop removal, before a second migration occurs. Second, there are other points in the season when the grower may find it optimal to change at least one pyriproxyfen application date, relative to when a second migration is not considered, but would observe the second immigration before the newly optimal application timing. In this situation, coordination has no value to the grower. Finally, there are other points in the season when the grower would not find it optimal to change the optimal application date, relative to the date calculated when a second invasion is not considered.

I analyze one second infestation date in detail for each of three categories. The first category contains a second infestation date for which a grower will find it optimal to change one or more application dates, but coordination is required in order for him to maximize profits from strawberry production. March 1 fits into this category. The second category includes a second infestation date for which a grower will find it optimal to change the timing of his pyriproxyfen applications, but no coordination is required in order for him to maximize profits. November 1 fits this category. The third category contains a second infestation date for which a grower will not find it optimal to change application dates and coordination will not be necessary to increase the profit from strawberry production. This includes January 1.

Whitefly immigrations due to host plant removal on March 1 in an adjacent field require coordination for a fall-planted strawberry grower to maximize profits. Profits from strawberry production can be increased by coordinating management activities due to a March 1 adult whitefly immigration, which corresponds to a celery harvest. If two pyriproxyfen treatments are made during the season, and the effects of the March 1 immigration are considered, the optimal timing of the first application changes from November 1 to November 8, and the optimal timing of the second application changes from the week of January 13 to the week of January 6. Even though neither of the application dates changes much, profits increase by changing the timing of the applications. However, the growers need to coordinate in order for the strawberry grower to identify the optimal application dates, because both pyriproxyfen applications occur before the celery harvest. An information exchange between growers is the only means for a strawberry grower to know how migrations of adult whiteflies from the celery field will affect optimal pyriproxyfen application dates for his strawberry field. February 1 and May 1 also fit into this category.

I now discuss a case when a grower would find it optimal to change one or more application dates, relative to those calculated when a second immigration is not considered, but would not have to coordinate with adjacent growers because he would observe immigration prior to adjusting management decisions: a second migration on November 1. If two pyriproxyfen treatments are made, the weeks of November 1 and December 30 are optimal. The grower can observe the development of the combined whitefly application before making a decision about when to make a second application. In this case, the grower does not need to exchange information with the celery grower since the November 1 celery harvest and ensuing greenhouse whitefly migration are observed prior to the optimal second application. The optimal timing of the application changes because the December 30 application reduces the combined nymph populations from the eggs laid by the first and second immigrations by more than the January 13 application. December 1 and 15 also fit into this category.

Finally, I discuss a case when a second immigration of adult whiteflies would not induce a grower to change the timing of his pyriproxyfen applications. As a representative example, I discuss a second adult whitefly immigration into a fall-planted field after removal of a summer-planted strawberry field around January 1. I find that if a second adult whitefly infestation occurs around January 1, the optimal weeks for two pyriproxyfen applications remained November 1 and January 13, as when a second immigration is not considered. Applications at these times resulted in the highest profits for the fall-planted field. In this case, this program reduces the February, early-March adult whitefly population by more than waiting to make the second application. This occurs because the pyriproxyfen application kills enough of the eggs from both the original and secondary immigration of adult whiteflies to make it preferable to any other time. In addition, the cooler temperatures at this time slow egg production, making the combined effect of the January 13 application on the adult and egg population more important than the more powerful effect of a later application on the nymph population. Members of the Whitefly Action Committee confirmed this interpretation of the data (Benchwick, 2005; Ishida, 2005; Malone, 2005). February 15, March 15, April 1 and 15, and May 15 also fit into this category.

The analysis in this section shows that pest management decisions in one field affect the profits from producing fall-planted strawberries in an adjacent field. I have shown that strawberry growers would either make no changes to his pyriproxyfen application timing due to a secondary adult whitefly immigration; will find it optimal to change the timing, but would not need to coordinate with adjacent growers to do so; or will find it optimal to change the timing and will need to coordinate with adjacent growers. When a grower finds it optimal to make these changes, the amount of coordination required is limited–the only requirement is that information related to field management be shared among growers of whitefly host crops.

4.1.2 Three Pyriproxyfen Applications

In this section, I assess the effect of second whitefly infestations on the optimal timing of three pyriproxyfen applications (after an imidacloprid application) on fall-planted strawberries in the Oxnard area. The purpose of this analysis is to assess whether or not allowing three pyriproxyfen applications would substitute for coordinated pest management by eliminating an increase in profit through sharing information. As in the previous subsection, the results of this analysis show multiple whitefly immigrations may make it optimal to change the timing of an pyriproxyfen application. As in the two-application case, the coordination required (in order for growers of fall-planted strawberries to realize this) changes with the timing of the second infestation. The ability to recognize any divergence between the optimal private and optimal multi-producer management responses to an invasive species informs the policymaker about the benefits of coordination. This, in turn, allows the policymaker to evaluate the benefits of instituting mandatory coordination and compare them to its costs, if voluntary coordination does not occur.

Again, I analyze one second infestation date in detail for each of three categories as in the previous subsection. As in the two-application case, March 1 and February 1 fit into the first category, and February 15 has moved into it. Also, as in the two-application case, December 1 and 15 fit the second category, but November 1 drops out and May 15 is now included. The final category includes March 15, and April 1 and 15 as in the two-application case, and November 1 and May 1 are now included.

To illustrate the first category, I examine the effects of a second immigration on March 1, due to a celery harvest, on optimal pyriproxyfen application timing. This resulted in optimal applications during the weeks of November 1, January 6, and March 5. Although the immigration will not have occurred yet, it is optimal to make the second application later by a week (January 6 instead of December 30) and the third made later by over a month (March 5 instead of January 29), relative to the single-field model. No coordination between adjacent growers would be required prior to making the first pyriproxyfen application. However, since the grower may not be able to observe the migration before having to change the timing of the second application, coordination must occur, through information exchange, prior to the second and third applications in order for the strawberry grower to maximize profits.[13] The reason for the change in application timing is that making the second application later kills nymphs that will mature later, preserving yields when plants produce berries the most rapidly (during March through May in the Oxnard area) by reducing the adult population at that time. It is optimal to make the third application later because it slightly reduces the recently-arrived adult whitefly population and kills the eggs they would already have oviposited. Since the fresh season ends soon after this application (most plants are producing for the processed berry market by May), this result indicates that the optimal timings emphasize protecting the fresh, rather than processed, harvest.

To illustrate the second category, I examine the case of a celery harvest occurring around November 1. Coordination was unnecessary, as in the two-application case. An immigration at this date resulted in the optimal timing of the third application being one week later, around February 5 instead of January 29, when the effects of a second immigration are included in a grower's decision. The change in optimal timing can be explained by a larger, but delayed population peak caused by the second immigration of adult whiteflies, which is managed by the later application date. Although the grower would find it optimal to change the timing of the second application because of the second immigration, the grower can rely on his own observation to make this change, and no coordination is needed.

For second infestation dates in the third category, optimal application dates do not change as a result of the second infestation. Consider the removal of a summer-planted strawberry field around January 1 in an adjacent field. It does not change the optimal timing for pyriproxyfen applications in a fall-planted field; applications are done the weeks of November 1, January 6, and February 5. In contrast with the results in section 4.1.1, these simulations indicate that when three applications are available it can occasionally be optimal to make the second application soon after the second immigration, rather than waiting for the population to grow and making the application right before a projected population peak.

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[13] A second migration on February 1 had the same qualitative result, just as in the two-application case.

I now examine whether the availability of a third application changed whether or not fall-planted strawberry growers would voluntarily coordinate their whitefly management decisions. There are two ways of assessing its effect: for the season as a whole and for individual weeks. First, because there are still second migration weeks for which coordination increases the strawberry grower's profits, a third application does not eliminate the benefit of coordination. Second, the benefits of coordination changed for some second migration weeks.

Four dates changed the category for the required amount of coordination necessary to maximize profits. First, a second migration on November 1 changed from it being optimal to change application dates, but not necessarily exchange information, to no difference in the application dates calculated with or without considering a second immigration. In this case, making any applications earlier, as when only two applications are permitted, is not necessary since the third application is able to optimally reduce the population. The application on May 1 changed in the same manner.

Second, a second migration on February 15 changed from it being optimal to not change any application dates and to not coordinate, to it being optimal to change an application date and needed to coordinate in order to maximize profits. The second and third applications must now be done on December 1 and January 6, which are both prior to the second migration. This series of applications reduces the adult whitefly population slightly, compared to the series of applications calculated without including the effect of a second migration, which will preserve more fruit during this period of increased production.

Third, a second migration on May 15 changed from it being optimal to not change any application dates and to not coordinate, to it being optimal to change an application date but not necessary to coordinate in order to maximize profits. In this case, allowing a third application makes it valuable to rearrange the application timing so that the adult whitefly population is, again, reduced during April. This change, however, allows the adult whitefly population to be higher in January than in the privately optimal case.

Because cases exist when a fall-planted strawberry grower would find it optimal to change the timing of their pyriproxyfen applications and coordination will be needed, relaxing the pyriproxyfen use restrictions to allow three pyriproxyfen applications, as opposed to two, does not remove the possibility for increased profits by coordinating; communication may still be required. On the other hand, as these results show, allowing more applications changes the times of the growing season when coordination is required to maximize profits.

4.2 Cooperative Invasive Pest Management

The analysis in section 4.1 demonstrates that a relationship exists between the expected value of learning about whitefly immigration dates and the incentive to coordinate management decisions. To maximize profits, the grower must form an expectation about the timing of future whitefly infestations and calculate any changes these will make on the optimal timing of pyriproxyfen applications. When a grower expects that a future infestation will change the optimal timing of his pyriproxyfen application, it is possible that the only way for him to verify this is to communicate with neighboring growers. Alternatively, if the grower expects that these infestations will occur at other times of the growing season, communicating with neighboring growers is irrelevant because the optimal treatment dates either do not change or the grower will calculate the changes to the optimal pyriproxyfen application times on his own. In the absence of any information, there is a positive expected benefit of communicating for the strawberry grower, because in some cases knowing the likely date of a future infestation and adjusting application dates accordingly will increase profits.

The exchange of information regarding the presence of whiteflies in adjacent fields, and the likely time of their migration, can be done via informal communication among pest control advisors or growers. When the grower finds it optimal to change pyriproxyfen application dates, and cannot make this calculation based on his own observation, this communication must take place at or before the first application date. The incremental costs associated with the transfer of this information could be covered by a surcharge to strawberry growers for asking pest control advisors (PCAs) to observe the edges of adjacent fields, in addition to their usual services of observing the pest conditions in the grower's fields (Benchwick, 2005; Ishida, 2005). This method assumes that PCAs will know the planting and removal dates of specific fields, which is common practice. Alternatively, policymakers may desire to enact a formal coordination requirement, administered by some type of government entity, if informal methods of data gathering and communication do not emerge due to transactions costs or other coordination problems.

In either the formal or informal case, an information exchange program can only be economically justified if the benefit from the exchange is at least as great as its cost. The benefit from such a program comes from avoiding increased control costs and reducing foregone yields. These could be accrued over one or several years.

To estimate the costs of such a program, one could use the notification requirements associated with methyl bromide application in California as an example. The direct costs of the methyl bromide notification program are negligible. In this program, growers are required to formally notify the occupants of property within a specified range of the application area of the timing of the methyl bromide application. Carter et al. (2005) estimated that the cost of a typical methyl bromide notification ranged between $2 and $10. The amount of time required for assembling and distributing information to notify adjacent growers about anticipated crop planting and removal dates would be comparable to assembling and distributing methyl bromide application notices. These notification costs represent between 0.01% and 0.03% of the value of the yield from an untreated acre of strawberries, given the average weekly price per pound of strawberries in the Oxnard area between 1999 and 2003. These costs are negligible to strawberry growers.

There are two reasons why information exchange may emerge voluntarily. First, coordination can be beneficial to strawberry growers producing in fields adjacent to ones with alternative host crops which generate populations of migrating adult whiteflies at certain times of the year. As shown, because adult whiteflies migrate across fields, the management decisions of one grower affect other growers in the area. The analysis shown in section 4.1 demonstrates that if strawberry growers use information on whitefly immigration dates to adjust pyriproxyfen application timing, profits may increase relative to the case when information is not shared. This suggests that if growers of adjacent fields did not provide information for free, strawberry growers may be willing to pay for information in order to make optimally timed pesticide applications.

A second condition favoring voluntary coordination is that the net benefits from free-riding on the coordination efforts of others are small to growers of whitefly host crops and may even be negative. Free-riding consists of benefiting from reduced whitefly populations as other growers share and utilize information about the timing of adult whitefly population migrations, while not sharing similar information with adjacent growers of host crops themselves. The benefits to free-riding include the alternative use of resources used for the cost of sharing information among growers. The result of this, however, is that the neighbor will not make optimally timed pyriproxyfen applications, leading to a larger-than-optimal whitefly population at the end of the season. Other things equal, this results in a larger adult population migrating back into the free-riding grower's field at a future date, leading to foregone yields and increased control costs. When these costs exceed that of coordination, the net benefits to free-riding are negative.

5 Conclusion

In this report, I have used the bioeconomic model developed in this study to determine whether profits could be increased through coordinated whitefly management decisions when externalities occur as a result of spatial relationships among growers. I found that two sets of conditions exist, regardless of the current pyriproxyfen use restrictions, under which coordination could increase profits. In some cases, the results showed growers need to coordinate, via sharing information about the timing of the field management decisions, in order to maximize profits in their own field. In other cases, the results indicate that growers could observe the decisions of adjacent growers prior to making changes to their subsequent management decisions, making coordination unnecessary; however, if these observations could not be made, coordination would again be required. On the other hand, a third set of conditions would not increase profits: there are times of the growing season when a fall-planted strawberry grower would never find it optimal to change the timing of his pyriproxyfen applications, relative to the results obtained from the single-field model. In these cases, coordination has no value to the grower.

The results of this study have three important policy implications. First, permitting more applications of pesticides per year will not necessarily substitute for coordination among growers when seeking to control invasive species, such as the greenhouse whitefly. The analysis comparing optimal grower decisions when the two-application limit for pyriproxyfen is imposed and when it is relaxed demonstrated that greater profits can be obtained through coordination in either case. The use of the methodology was essential, therefore, in identifying the incremental effects on producer behavior of changes in environmental regulations designed to manage an invasive species.

The second policy implication is that it is not always necessary to create a central agency for controlling the economic effects of invasive species. For the case of fall-planted strawberry growers in the Oxnard area, I used a bioeconomic model of whitefly management to determine when they would be willing to voluntarily coordinate their whitefly management efforts with growers of adjacent host crops. These results help explain the development of the Whitefly Action Committee and the willingness of fall-planted strawberry growers to participate in it. Our analysis shows that in the cases where coordination is beneficial, fall-planted strawberry growers need to obtain information from growers of adjacent fields prior to the first application date, whether or not an infestation ultimately occurs. Furthermore, there were virtually no benefits to free-riding for fall-planted strawberry growers. In fact, they would find it profitable to provide such information to their neighbors themselves, in order to reduce the expected future whitefly population. When these conditions exist and adjacent growers find it profitable to provide the necessary information, voluntary coordination may be possible.

On the other hand, if growers of alternative host crops, whose profits are very small relative to those of fall-planted strawberry growers, do not find it profit-maximizing to exchange information when the cost of coordination exceeds its benefits, then two situations could occur. First, the growers could agree on a price the strawberry grower could pay to the grower of the adjacent field to compensate them for any effort to gather the required information. Second, if transactions costs are too great for voluntary coordination to arise, policymakers may increase social welfare by mandating grower participation in an information exchange managed by the university cooperative extension, a regulatory agency such as the California Department of Agriculture, or another government entity. The optimal design of such a program is outside the scope of this analysis. These results simply suggest that there is a possibility that a mandatory program may increase social welfare under certain conditions. Again, however, the methodology presented in this study was essential to identifying elements of such a program.

The analysis in this report demonstrates a method that policymakers can use to obtain information about the likelihood of growers successfully developing voluntary coordination measures. I showed that a bioeconomic model can enable an analyst to evaluate a series of explanations for how a set of agricultural producers behave and then provide a reasonable case for inferring that others in the same situation may act similarly. For example, the results explained why Oxnard area strawberry growers may or may not voluntarily coordinate their whitefly management strategies using the bioeconomic model developed in this study. All the available biological and economic information related to the greenhouse whitefly/strawberry interaction was incorporated into the model, but its value is not limited to these variables. An analyst can incorporate other factors identified by growers or policymakers as essential determinants of the emergence of voluntary coordination into the model and evaluate their contributions through sensitivity analysis, in order to see whether or not these are likely to affect the conclusion. In this way, the model both predicts behavior and provides a means of identifying future data collection priorities.

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