Spatio-Temporal Modeling of Asian Citrus Canker Risks: Implications for Insurance and Indemnification Fund Models*

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Abstract

Asiatic citrus canker is an infectious disease that is a significant hazard to commercial citrus production in Florida. Our paper examines spatio-temporal models of the risks of citrus canker transmission. The State of Florida implemented an inspection program that checks every commercial grove several times each year. We use data from over 338,000 inspections over the 1998-2004 period to evaluate the risks associated with canker infection. Simple models describing the risks of infection are used to evaluate risks and associated indemnity/insurance fund contribution rates. Fruit type, grove size, and a history of recent infections in neighboring areas are found to be important determinants of canker infection risks. Conditional risks are estimated from the models and are used to price annual contracts which would pay producers a pre-specified indemnity in the event that their grove is found to be infected with canker.

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1 Introduction

Florida had 748,555 acres of commercial groves in 2004 with the value of sales on-tree an estimated \$745.963 million for 2003-2004 (Florida Agricultural Statistics 2005). Florida is the largest citrus growing state and accounts for 79% of total U.S. citrus production. Figure 1 illustrates that the estimated value of citrus production in Florida in 2004, represents a significant reduction from the most recent high of \$1,108.523 million in 1999-2000—a decline of 32.7%. Total production in the 2003-04 crop year amounted to 291.8 million boxes with 242 million boxes of oranges (82.9%), 40.9 million boxes of grapefruit (14.0%), and 8.9 million boxes of other types of fruit (3.1%) (Florida Agricultural Statistics 2005).

Citrus canker disease affects plants in varieties of citrus species and citrus relatives. The following citrus species have been identified as being "highly susceptible:" grapefruit, key/Mexican lime, Palastine sweet lime, and trifoliate citrus, sweet orange cultivars: Hamlin, Navel, and Pineapple (Schubert, Gottwald, Rizvi, Graham, Sun and Dixon 2001). The disease is caused by a bacterial pathogen, *Xanthomonas axonopodis pv. citri*. Before the most recent detection in 1995, the disease was found in the U.S. on two previous occasions, in Florida and other Gulf Coast citrus growing states in 1910 and on the Gulf Coast of Florida in 1986. Both of these previous infestations were reportedly resolved by eradication programs conducted by USDA and the affected states (USDA-APHIS 2005a).

The recent eradication program in Florida began in 1995 and evolved into a program which involves separate infestations and different strains over numerous Florida counties. This infestation of an Asiatic strain of citrus canker has been traced to originate in a residential area near Miami International Airport. Additional detections from this infestation culminated in an eradication program that included most of Miami-Dade County by 1998. Further, in May 1997 in what is believed to be a separate infestation, a different Asiatic citrus canker strain (thought to be connected to an earlier 1986 infestation) was discovered in Manatee County in both residential citrus and commercial growing areas (USDA-APHIS 2005a).

Plants infected by citrus canker develop lesions on leaves, stems, and fruit. These lesions ooze bacterial cells, making canker highly contagious. Canker can be spread rapidly by wind driven rain, movement of equipment or workers that have come into contact with infected trees, or movement of infected or contaminated plants. These vectors of transmission, involving significant weather events and idiosyncratic movements of workers or people carrying contaminated plants, makes containment a significant challenge. Once infection occurs it can take anywhere from 14 to 60 or more days for symptoms to appear. The bacteria can remain viable in lesions for several months (USDA-APHIS 2005a).

This most recent outbreak of citrus canker presents an ideal case study for modeling risk since extensive data relating to transmission and the factors underlying risks have been collected. The State of Florida implemented an inspection program that checked every commercial grove annually, with some groves being inspected several times each year. We use data from over 338,000 inspections over the 1998-2004 period in an empirical model that identifies risks, potential losses, and appropriate premiums and contribution rates for an indemnification program. Simple probability models for the risks of infection are used to evaluate risks and associated indemnity/insurance fund contribution rates. The risks are estimated for annual contracts which would pay producers a pre-specified indemnity in the event that their grove is found to be infected with canker. Implications for more sophisticated models of spatial/temporal risk relationships are also discussed.

2 The History of Citrus Canker Outbreaks

Gottwald, Hughes, Graham, Sun and Riley (2001) describe how citrus canker has a long history dating back to the 1910s, when it entered from improved seedlings from Japan. Declared eradicated by 1993, a new infection was found in Mantee County, Florida in the late 1980s. This infection was thought to have been eradicated by 1994. Gottwald et al. (2001) explain that a new and separate outbreak occurred in urban Miami in 1995 and, at around the same time, a reemergence occurred in the same area where the outbreak occurred in the 1980s. Gottwald et al. (2001) estimate that the 1995 Miami discovery near the airport spread from an initial 14 square mile area to over 1,005 square miles in the metropolitan area plus an additional 260 square miles of urban and commercial citrus areas through the state. They point out that genomic analysis of bacterial isolates revealed that the majority of this outbreak was largely associated with the Miami discovery and therefore human-assisted movement must have been a factor in its transmission. Furthermore, in early 2000, a third distinct isolate of Asiatic citrus canker was identified in Palm Beach County. Therefore, there are at least three types of citrus canker that have been introduced in Florida in the most recent two decades (Gottwald et al. 2001). The USDA (USDA-APHIS 2005b) provides a brief chronology of key events related to citrus canker over the period 1995 to 2003. This time-line consists of new discoveries of citrus canker over time, implementation of an eradication program, and legal challenges to this eradication program. In the discussion that follows, we highlight some of the key events as reported and identified by the USDA (USDA-APHIS 2005b).

In response to the September 1995 discovery of citrus canker in a residential area near Miami International Airport, the state of Florida and the USDA began administering surveys and implementing regulatory and control measures in the Miami-Dade County area. By June 1998, citrus canker had been found in Immokalee and in residential areas of Collier County. These infections were found to be related to the strain found earlier in Miami. Further, in the previous year, commercial groves in Manatee County were found to be infected and these infections were traced back to the strain that caused the 1986-94 infestations. In February 1999, an interim rule identified a federal quarantine area which had been expanded since the 1995 find to include 507 square miles of Broward and Miami-Dade counties, 68 square miles of Manatee county, and 30 square miles of Collier county. A final rule that was published in July 1999 affirmed previous interim regulations that established a federal quarantine area encompassing Miami-Dade, Broward, Manatee, and Collier Counties in Florida (USDA-APHIS 2005b).

Despite these quarantine efforts, the spread continued with additional discoveries of the Asiatic strain of citrus canker in residential areas of Hillsborough County in November 1999 and in lime groves in southern Dade County in January 2000. Schubert et al. (2001) reported that these discoveries led to destruction of almost half of the 4,000 acres of limes in the area due to exposure or infection. It was suspected that the disease was transferred via human activities from nearby residential areas to the north, with the oldest infections being detected in the highly susceptible pummelo fruit being grown in the vicinity of commercial lime groves. In February 2000, the Florida Commissioner of Agriculture announced the implementation of a significant eradication program that would go into effect April 1, 2000. The key components of this program as described in

USDA-APHIS (2005b) were as follows:

- decontamination of workers and equipment moving between groves;
- removal of all trees within a 1,900 feet radius of an infected tree;
- establishment of a replacement program where residents whose trees that must be cut will be entitled to $100 voucher for the cost of a non-citrus tree; and
- establishment of a public relations program.

In April 2000, several of the quarantine areas were also expanded (the Miami-Dade-Broward area and Collier County) and a new quarantine area of 106 square miles was established in Hendry County. At the same time, a sentinel survey program was initiated and there was a discovery of a third Asiatic strain of citrus canker on key limes in a Palm Beach residential area.

In October 2000, the Broward County Court cited improper rule-making and stopped the cutting of exposed trees within 1,900 feet of infected trees. This was followed by an appropriation of $8 million in state funds in November to restore homeowners' property losses. These funds were in addition to the $100 vouchers already available for each tree lost. This also preceded proposed compensation to commercial growers for lost income due to the emergency control measures. In July 2001, a state administrative court found that the Florida Department of Agriculture exceeded its authority and therefore had to undergo an evaluation of its process of rule-making concerning the 1,900 feet cutting policy. Public hearings were held and in November 2001 a new rule extending the cutting of trees in proximity to exposed trees from 125 feet to 1,900 feet was implemented. These legislative efforts were challenged by Broward County, who filed briefs in administrative court during the same month countering the new rule. In March 2002, the state legislature passed a bill which was signed by the Governor of Florida, authorizing the removal of all citrus trees within the 1,900 feet area of an infected tree and permitting the use of blank search warrants. The Department of Agriculture and Consumer Services appealed the judgement in April, 2002. In May 2002, a Broward county Circuit Court judge ruled that the eradication program which involved cutting exposed trees and using blank search warrants was unconstitutional since it violated constitutional search and seizure laws. At the same time, a Miami nursery won a restraining order to prevent the Department of Agriculture from removing calamondin trees. The significant amount of pending legal action led Florida Department of Agriculture officials to request permission to cut exposed trees in Palm Beach County in June 2002.

In July 2002, further litigious events transpired with the 4th District Court of Appeal ruling that attorneys could bypass the Court and go straight to the State Supreme Court due to the importance of the matter and its impact on the public. The Supreme Court in turn rejected this ruling and sent the action to the district court of appeals. Meanwhile in August 2002, citrus canker was discovered in Lee County, making fourteen counties that had positive finds since the 1995 discovery. The discovery was followed by the District Court of Appeals certifying a class action lawsuit by those who had be affected by the eradication program and who were seeking damages. By October 2002, new infections were found in Sarasota and Okeechobee Counties and a judge signed search warrants allowing mandatory inspections. In November and December of 2002, new quarantine areas were established in Orange and Lee Counties while areas in Collier and Hendry Counties were reduced in size.

3 Citrus Canker Programs

3.1 Tree Replacement Payments

An interim rule was published on October 2000 providing eligible producers of commercial citrus payments to replace trees removed because of citrus canker (USDA-APHIS 2000). The payment was in the amount of $26 per tree, up to a maximum of between $2,704 and $4,004 per acre depending on the variety (Table 1). Per-acre payment caps were determined by the $26 per tree amount multiplied by the average number of trees per acre for a particular variety. This $26 payment per tree was determined by the USDAs Risk Management Agency (RMA) and took into consideration the costs of land preparation, replacement trees, labor for planting, and maintenance until the trees became productive (USDA-APHIS 2000). It was estimated that this program would compensate producers approximately $18.8 million with the payment of $26 per tree and an estimated 723,800 trees having been destroyed. However, the actual cost is estimated to be less because of the per-acre cap on payments.

3.2 Lost Production Payments

Tree replacement payments began in 2000 to compensate owners of commercial citrus groves who lost trees because of citrus canker. The lost production payments went beyond the loss associated with the cost of the tree and compensated producers for the forgone income caused by the removal of commercial citrus trees to control canker. Owners of commercial citrus groves were made eligible if trees were removed because of a public order between 1986 and 1990 or on or after September, 28, 2005 (USDA-APHIS 2002). Production payments are paid on a per-acre basis and vary across types of citrus trees, as is shown in Table 1. Limes have the largest payment at $6,503 per acre for lost production and a maximum payment of $4,004 per acre for tree replacement. Next is oranges, valencia oranges, and tangerines with a payment of $6,446 per acre for lost production and a maximum payment of $3,198 per acre for tree replacement. Payments on navel oranges are slightly less with $6,384 per acre for lost production and a maximum of $3,068 per acre for tree replacement. Grapefuit and other mixed citrus fruits had considerably lower payment levels, with a lost production payment of $3,342 per acre and a maximum tree replacement payment of $2,704 per acre.

The rationale given for establishing production payments on a per-acre basis was that fruit output per acre is about the same, regardless of the number of trees. New groves have more, smaller and less productive trees, whereas older groves have fewer but larger and more productive trees. The per-acre amount is meant to reflect the approximate per-acre net income for each fruit variety, calculated by determining the revenue per tree and subtracting the production costs per tree to arrive at a net cash flow per tree which is then multiplied by the number of trees per acre. USDA-APHIS (2002) explains that this per-acre value was calculated using a life-cycle approach with revenues and costs representing the productive life of a replanted grove. For limes this is 25 years. For other citrus varieties, the productive life was established at 36 years. The information utilized in these calculations employed data collected from the Florida Agricultural Statistics Service and the University of Floridas Institute for Food and Agricultural Sciences (UF-IFAS). If a producer purchased Asiatic citrus canker (ACC) crop insurance coverage and received an indemnity payment, lost production payments would be reduced by the amount of the indemnity payment. If the producer failed to purchase ACC if it was available, the per-acre production payment was reduced by 5%.

3.3 Crop Insurance

The Florida Fruit Tree Pilot Program began in 1996 and covered Dade, Highlands, Martin, Palm Beach, and Polk Counties. Insurance was provided for the following tree types: orange, grapefruit, lemon, limes, all other citrus, avocados, carambolas, and mangos. This policy is specifically aimed at tree stock rather than the fruit (another policy provides such coverage) and provides protection for damage to or destruction of trees. In 1998, a separate policy was developed for avocado and mango trees, which were dropped from the Florida Fruit Tree policy.

The policy initially insured against causes of loss that included excessive moisture and freeze or wind damage. An indemnity is triggered when damage to trees exceeds the chosen deductible. Coverage levels range from 50 to 75% of the reference maximum price per tree. The insurance period ends the earlier of November 20 or upon determination of total destruction of insured trees (USDA-RMA 2005). In October 1999, the USDA-RMA announced that the Florida Fruit Tree Pilot Crop Insurance program for the 2000 crop year would be revised to allow producers to insure against losses to citrus trees arising from Asiatic Citrus Canker (ACC). The coverage area was expanded to 24 additional counties, making the pilot available to most commercial tree growers in an area that encompassed 29 counties. The ACC coverage was introduced as part of the standard policy but there are two sets of perils, standard and ACC, each determined separately. A producer in a county located without a quarantine zone qualifies for ACC coverage automatically. A producer in a county with a quarantine zone must obtain an ACC underwriting certification before coverage for ACC will be attached.

Table 2 documents that there was a significant increase in liabilities across the tree types and delivery methods (RBUP, CAT) in 1999-2005.[1] In 1999, total liabilities were only $156.8 million for all citrus in the Florida Fruit Tree policy. By 2005, this liability had increased to $1.141 billion. Initially in 1999, the most prevalent mode of delivery was through CAT coverage, which accounted for 91% of total liabilities compared with the higher levels of coverage (RBUP), which only accounted for 9%. The revisions in 2000 that included ACC as an insurable cause of loss transformed the preferred delivery. That is, a much larger proportion of trees were insured at higher levels of coverage than that provided by CAT, especially for the most susceptible citrus

[1] RBUP is re-insured buy-up coverage which is higher levels of coverage above CAT (levels above 50% of yield and 60% of price). CAT refers to catastrophic insurance coverage, which is provided to producers at a highly subsidized rate (consisting of only a small administrative fee).

varieties—limes and grapefruits. The inclusion of ACC as an insurable cause of loss as well as the additional 24 counties that were included in 2000 explains the dramatic increase in liabilities which rose from $156.8 million in 1999 to $697.3 million in 2000. By 2001, RBUP was the preferred delivery mode and this has remained the case with 63.4% of liabilities being insured with RBUP in 2005.

Table 2 also documents another important characteristic of the current outbreak of citrus canker which is important to our empirical modeling work in later sections. Comparison of loss ratios across tree types suggests that some varieties are more susceptible and therefore more likely to be infected and receive an indemnity under this policy. Limes are the most notable, with loss ratios of 14.23 in 2000, 4.38 in 2001, 12.85 in 2002, and 6.63 in 2003 for the RBUP delivery.[2] These very large loss ratios as well as the rapidly declining total liability level for limes (which were $6.9 million in 2000 but only $83 thousand in 2005) reveals how adversely affected the lime groves have been by the current outbreak of citrus canker. The less susceptible oranges, which also happen to account for the largest share of total liability, have not had loss ratios for either delivery method that exceeded 1.0 in any insurance period since 1999, with 2005 being the most adversely affected insurance period with loss ratios of 0.81 for RBUP and 0.88 for CAT. These liabilities and loss ratios highlight the importance of recognizing differences in the relative susceptibility across varieties as well as the spatial characteristics of the groves of different varieties when modeling the spatial and temporal risks of transmission.

4 Biological Research on Citrus Canker

To model the spatial and temporal aspects of the risks of citrus canker transmission, it is critical to have a perspective on the biological research that has been conducted on citrus canker. In particular it is important to understand vectors of infection, the symptoms, rates of dispersion, and other important characteristics which impact the spatial and temporal aspects of infection. In the discussion that follows, some of the key scientific research results on these topics are briefly discussed. Much of this research can be characterized as investigating a within-grove (or nursery) spread as opposed to spread across groves. The results of this research are useful in that they help

[2] Loss ratios represent dollars paid out in indemnities per dollar paid in premiums.

to ascertain how the disease is spread. However, they are not directly applicable to our modeling effort in that we focus on the spread of the disease on a larger scale (such as across groves). The following brief discussion is by no means a complete review of the existing scientific knowledge on canker. Rather, it highlights some of the important findings that are pertinent to the empirical modeling in later sections of the chapter.

Graham, Gottwald, Cubero and Achor (2004) described the symptoms of citrus canker as distinct raised, necrotic lesions (localized death of living tissue) on the fruits, stems, and leaves. The epidemiology involves bacteria spreading from lesions during wet weather and being dispersed at short range by splash, at medium-long range by windblown rain, and at all ranges by human assistance. The damage to the crop involves blemished fruits and defoliation. Importantly, Graham et al. (2004) point out that there are limited measures to prevent the spread of the bacteria.[3] Any blemished fruits are unmarketable and restricted from entering the market. This prohibition of market access is more significant than the actual losses pertaining to the yield of the crop.

Bock, Parker and Gottwald (2005) used simulated, wind-driven rain splash to investigate the spread of the bacteria that causes citrus canker (*Xanthomonas axonopodis pv. citri*). The simulation involved electric blowers designed to generate turbulent wind and sprayer nozzles to produce water droplets entrained in the wind flow. Using this controlled environment, it was determined that citrus canker is readily dispersed in large quantities immediately after stimulus occurs. Furthermore, wind-driven splash was determined to have the capacity to disperse the inoculum for long periods and over a substantial distance.

Verniere, Gottwald and Provost (2003) investigated environmental and epidemic variables associated with disease expression under natural conditions on Reunion Island. This research found that tissue age rating at the time of infection was a good predictor of disease resulting from spray inoculation on fruits and leaves and also on fruits following a wound inoculation. Mature green stems and leaves were also found to be highly susceptible after wounding while buds and leaf scars expressed the lowest susceptibility. Furthermore, temperature was also a significant factor in determining disease development.

[3]Gottwald and Timmer (1995) did find that use of windbreaks and copper bactericide can significantly reduce the temporal disease increase and spatial spread of citrus canker over time, with the windbreak being most effective.

Gottwald, Sun, Riley, Graham, Ferrandino and Taylor (2002) investigated the spread of citrus canker in urban areas of Miami in the context of the effectiveness of the practice of removing exposed trees within 125 feet of infected trees in eliminating further bacterial spread. Several results from this work are of interest. It was established that a broad continuum of distance for bacterial spread was possible with maximum distances ranging from 12 to 3,474 meters in a period of 30 days. In addition, it was determined that the disease was best visualized 107 days following rainstorms with wind. Finally, this work showed that rapid spread of disease occurred across the regions studied in response to rainstorms with wind, followed by a filling in of disease on remaining non-infected susceptible trees through time by less intense rain storms.

Gottwald, Reynolds, Campbell and Timmer (1992) compared spatial and spatio-temporal patterns of citrus canker infection in nurseries and groves in Argentina. This work involved innoculating the center plant in each plot with *Xanthomonas campestris pv. citri* and allowing the disease to progress for two growing seasons. Final disease incidence exceeded the 90% level in all three nurseries and reached 69% and 89% for orange and grapefruit groves, respectively. Study of the proximity patterns reveals that some noncontiguous elements indicated the formation of secondary foci. Further these noncontiguous elements remained until the last few assessments, made every 21 days, before they eroded and the proximity patterns generally became larger and contiguous.

4.1 Spatial and Temporal Aspects of Transmission

A key aspect of disease and pest contamination involves the spatial aspect of transmission. Pathways for transmission of diseases and pests generally have a spatial element. Thus, risks are highly correlated across space. In terms of modeling draws from distributions of yields in neighboring geographic regions, it is clear that yield realizations from one region are certainly expected to be highly correlated with those in neighboring areas. Spatial statistics play an important role in modeling the epidemiology of infectious diseases. An extensive literature, summarized by Alexander, Cartwright and McKinney (1988) and Rothenberg and Thacker (1992), has investigated spatial aspects of disease transmission. It is common in modeling spatial aspects of yield risk to assume that the correlation of risk declines with distance. This is certainly intuitive, though weather patterns are often directional and thus it is important that the directional aspects of spatial risk relationships be explicitly acknowledged when modeling the risks associated with invasive species contamination.

Gottwald et al. (2001) outlined how the scientific basis for the eradication program now in place was initially based on data for Argentina which indicated that canker could spread up to 105 feet with wind-driven rains. This led to an initial mandated removal and destruction of trees within a 125 foot radius; presumably the additional 20 feet was established as a precautionary measure. This 125 foot rule was ineffective and the disease continued to spread in urban areas and spread to several commercial citrus plantations in south Florida (Gottwald et al. (2001) citing Gottwald, Graham and Schubert (1997)). This failure of the 125 ft. rule called into question the validity of this rule for three specific reasons that were spelled out by Gottwald et al. (2001) and reproduced here:

- the spread of citrus canker in a central Florida grove in the early 1990s was as much as 2,600 feet in a rainstorm;
- catastrophic weather (hurricanes and tornadoes) was documented by surveys to spread bacterium up to 7 miles; and
- the failure of the 125 ft. rule in citrus groves and urban areas to reduce the progress of the disease.

This failure and need for better information on the spatial characteristics of the spread led to collaboration between the Citrus Canker Eradication Program (CCEP) and the USDA-ARS and UF-IFAS to investigate and quantify the spatial patterns and dispersal of pathogens in a subtropical urban Miami setting. Gottwald et al. (2001) revealed that this epidemiological study took 18 months to complete and involved 19,000 healthy and diseased dooryard citrus trees in four areas: three in Dade County and one in Broward County, accounting for about 10 square miles. Figure 1 in Gottwald et al. (2001) illustrates the severity and contagiousness of this disease, showing how a single infected dooryard tree can lead to 1,751 infected trees over 18 months in a region of 12 square kilometers (3 kilometers north to south and 4 kilometers east to west).

5 Risk Models and Insurance/Indemnity Fund Contracts

As we have noted, a number of government programs have been directed toward providing compensation for those citrus producers affected by citrus canker. In the case of disaster relief, the assistance has been of an ad-hoc nature, with state and federal policy makers providing disaster payments in response to larger scale infections. Current crop insurance programs have provided protection against tree losses resulting from canker infection. However, this protection has been part of an *all-risk* insurance plan. All-risk coverage may suffer from a number of shortcomings from the difficulties associated with measuring the risks from all possible hazards.[4]

An alternative to all-risk insurance and ad-hoc indemnification plans is a specific-peril plan of protection. In this case, the task of quantifying risks is limited to a single peril. Protection is offered only for losses caused by this peril and thus actuarial considerations are limited to modeling only the risks associated with the particular peril being covered. Examples of specific peril policies include hail, flood, and cancer insurance. It is often argued that such specific peril plans have an advantage in that it is easier to quantify the risks associated with a single hazard than to attempt to model the risks from all hazards, including those that may be unknown. Such an issue is especially pertinent to plant disease considerations, where the risks of new diseases that have not been previously experienced may be relevant.

The key element to any effective insurance or indemnification plan is comprehension of the risks associated with the hazards being covered. In insurance contracts, knowledge of this risk underlies the actuarially-fair insurance premium rate. The actuarially-fair rate corresponds to the rate (expressed as a percentage of total liability) that sets total premiums equal to total expected indemnities. For example, if I expect to pay $1,000 in a typical year on an insurance contract that covers up to $10,000 in total liability, the actuarially-fair premium rate will be 0.10 (or 10% as it is more commonly expressed).[5] In the case of an indemnification fund which could be funded by a levy (or tax) on producers, the actuarially-fair premium rate is analogous to the checkoff rate (again expressed as a percentage of total liability) that must be charged in order to equilibrate expected payouts with contributions into the indemnification fund.

The risk models needed to measure the actuarially-fair premium or checkoff rate usually are expressed in terms of the conditional probability density or cumulative distribution function underlying the outcomes being considered. For example, in the case of crop yield insurance, one is

[4]See Goodwin and Smith (1996) for a detailed discussion of contract design issues associated with all-risk crop insurance plans.

[5]Note that liability corresponds to payouts in a worst-case scenario. In other words, liability is defined by the limit on maximum indemnities. Premiums are typically expressed as the rate given by a percentage of total liability.

generally concerned with obtaining an estimate of the density describing crop yields. Consider an insurance plan that guarantees a certain proportion λ of expected yield μ. If yields y fall beneath the guarantee, losses will be compensated at a predetermined price of P. In this case, indemnities will be given by:

$$P \cdot max\{0, \lambda\mu - y\}. \tag{1}$$

It is convenient to express expected losses as a product of the probability of a loss and the expected level of y, conditional on y being below $\lambda\mu$. Without loss of generality, we can assume that all losses are paid at a price of one.[6] In this case,

$$E(Losses) = Pr(y < \lambda\mu)(\lambda\mu - E(y|y < \lambda\mu)), \tag{2}$$

where $E(\cdot)$ is the expectations operator and $Pr(\cdot)$ denotes the probability associated with the indicated event. If we denote the probability density function (pdf) of yields by $f(y)$, expected indemnity payouts will be given by:

$$E(Losses) = \int_0^{\lambda\mu} f(y)dy \left[\lambda\mu - \frac{\int_0^{\lambda\mu} yf(y)dy}{\int_0^{\lambda\mu} f(y)dy}\right], \tag{3}$$

where $\int_0^{\lambda\mu} f(y)dy$ is equivalent to the probability distribution function evaluated at $\lambda\mu$, which we denote as $F(\lambda\mu)$. The premium rate will be given by the ratio of $E(Losses)$ to total liability $\lambda\mu$:

$$Rate = \frac{E(Losses)}{\lambda\mu}. \tag{4}$$

In many insurance programs, loss occurs as an all-or-nothing event. For example, life insurance policies will pay a fixed amount only in the event of death, with no other provisions that could generate partial payments. Such structure (a simple bond program) simplifies the construction of insurance premium rates since the payout is predefined. In such a case, the expected loss is given by the product of the probability of a loss and the fixed payment made in the event of a loss. Likewise, the premium rate is equal to the probability of a loss occurring. Such a contract is suitable for situations such as the citrus canker case, where any exposure corresponds to a complete loss.

A number of important issues underlie such risk modeling problems. Specifically, a number of important questions pertain to the density function $f(y)$. A specific choice of the density function

[6] Note that insurance premium rates are transparent to the price that losses will be paid at, since liability and indemnities are scaled by the same price, such that the ratio is unaffected by price. In an operational setting, however, it is possible that risks could be endogenous to price due to moral hazard. If the price is too high, individuals may undertake actions to increase their likelihood of collecting indemnities. We assume that such endogenous risks do not occur and thus that moral hazard is not an issue.

must be made. Goodwin and Ker (2001) discuss specification issues related to the distributional assumptions that must be made in modeling insurance contract parameters. As they note, one may choose to employ nonparametric density estimation techniques in cases where prior information about the parametric family governing the data generating process is absent. Alternatively, a wide variety of parametric distributions are commonly applied to model parameters of insurance contracts. For example, crop yields commonly exhibit negative skewness, reflecting the natural biological constraints that govern maximum crop yields. Thus, a common choice for modeling crop yields is the beta distribution, which is capable of representing the negative skewness often observed for crop yields.

Recognition of the factors that loss events should be conditioned on is also an important component of risk models. For example, crop yields have exhibited significant trends over time and such trends must be explicitly recognized when assessing the risk of crops using data collected over time. Different crop practices are also an important determinant of risk. Irrigated crops typically have much lower yield risk than dryland production and thus any assessment of risk must be conditioned upon the crop production practice. To the extent that observable, deterministic factors are pertinent to risk, more accurate premium rates can be constructed by taking these factors into consideration. In the case of contracts to insure citrus canker risks, we know that factors such as fruit type and characteristics of the grove are important determinants of the risk of infection and thus models of risk should be conditioned on such factors in order to produce accurate assessments of risk.

There are a number of operational considerations that must be considered when contemplating an insurance or indemnification program. One important factor involves the insurance period. A common insurance period is the calendar or crop year, where the terms of a contract are set prior to the beginning of the year and protection begins and ends with the beginning and ending of the year. In our analysis, we assume an insurance period corresponding to a calendar year. The period of insurance is important to how one models risk since risks can only be conditioned on information available *prior to the beginning of the insurance period.* For example, it is widely recognized that hurricanes with their characteristic high winds and precipitation are an important causal factor related to citrus canker infection. However, in that it is impossible (or at least very difficult) to predict the occurrence of a hurricane at any single location in the following year, knowledge that prior infections were correlated with hurricane strikes is of little use in constructing insurance contracts. In contrast, we know that different fruit types have varying levels of infection risk. The type of fruit to be insured in year $t + 1$ is known at time t and thus the parameters of an insurance contract can be conditioned on fruit type.

An insurance contract must also specify the unit of insurance. Because of the diversification that comes with increasing size, risks are often lower as more aggregate units of insurance are defined. However, in cases such as citrus canker, where any exposure corresponds to a total loss, it is important that the unit be defined at a level consistent with the extent of loss upon exposure. Our data on canker inspections are given in terms of "multiblock" units, which roughly correspond to individual commercial citrus groves. Multiblock units in our data average 14.7 acres in size and range from 0.05 to 510 acres.

In measuring risk and specifying insurance contract parameters, one must also decide upon the level at which risks will be measured. Alternative levels of aggregation may vary in terms of the stability of the premium rates implied as well as the accuracy of individual rates. In light of the spatio-temporal aspects of infection risks, the relative rarity of canker infections, and the large number of multiblock observations, we utilize a degree of aggregation in our initial risk models.[7] We considered two possible levels of aggregation. A common geographic designation based upon political boundaries is the "Township-Range-Section" (TRS) definition. Townships are defined by township lines that run east and west every six miles, starting from a principal meridian and range lines that occur every six miles north and south of a principal meridian. Each 36 square mile township is then divided into 36 individual square mile sections. These designations were often determined many years ago as land was initially surveyed and thus may be subject to a number of errors or may reflect other difficulties associated with the initial surveys.

The dispersion of multiblock units used in our analysis and the TRS boundary lines of Florida is presented in Figure 2 below. Multiblock units, representing commercial citrus groves, are identified by the small shaded areas. The TRS boundaries are also identified. A limitation associated with using the TRS boundaries to identify insurable units is immediately obvious—some of the multiblock units are located outside of townships. This occurs in South Florida. The irregularity in the size and shape of TRS units may also make their use for defining units of homogeneous risk

[7] This aggregation is relaxed below, where we consider conditional risks at the multiblock level.

questionable.

In light of the limitations associated with the TRS units, we chose to identify our own insurable units based on an evenly spaced grid that covers the entire commercial citrus growing region of Florida. We chose a grid defined by 10km^2 units. The resulting grid is presented in Figure 3. As is true of the TRS designations, the groupings are ad hoc and other possible group definitions could have advantages. However, this approach was compared to grids of alternative sizes and found to perform well in the analysis which follows and to produce robust results.

Finally, our approach requires that we adequately incorporate any measurable factors that can be used to condition the risk of infection. Recall that only those factors that can be measured prior to the beginning of the insurance period are useful in conditioning the risk of infection. An important aspect of citrus canker, as with any infection disease, is that infection is spread through exposure to the infectious bacteria. We know that infection risk is subject to important spatial and temporal correlation factors. In particular, proximity in a spatial or temporal sense to existing infections raises the likelihood that a grove will be infected. We capture this relationship by considering the infections recorded in the previous year in all units having centroids that lie within 30 km of the centroid of the unit in question.[8]

Under these assumptions, we can view our risk modeling approach to involve attempts to measure the conditional probability associated with citrus canker infection. This conditional probability can be expressed as:

$$Pr(y_{it}) = F(y_{it}|y_{jt-1}, \ldots, y_{kt-1}, Z_{it}) + \epsilon_{it}, \tag{5}$$

where $Pr(y_{it})$ corresponds to the probability associated with the event y_{it} (representing one or more canker infections in unit i in year t), y_{jt-1} is the infection status of neighboring unit j in year $t-1$, Z_{it} represents other predetermined factors conceptually relevant to the likelihood of canker infection, and ϵ_{it} is a random residual error.

In order to make the transition to an empirical analysis, we must choose specific empirical models of the likelihood of infection. Our data are described in detail in the next section. Our measure of infection is the status of a particular multiblock unit at the time of its inspection—a discrete 0/1 indicator. In that we are applying the models to our aggregated 10km^2 units, our

[8]The geographic centroid is the "center of gravity" of a geographic shape. In geometric terms, the centroid is the point at which a two-dimensional, planar shape would balance. In our units, the centroids are the exact centers of the 10km^2 units.

measure of infection for the aggregate unit is the simple count of infections within the unit. Given this measure of infection, we adopt two separate approaches to modeling the risk of infection. In the first, we consider probit models of the probability that one or more infections exist within a unit over a calendar year period. Thus, we model:

$$Pr(d_{it} = 1) = F(X\beta) \quad \text{and} \quad Pr(d_{it} = 0) = 1 - F(X\beta) \tag{6}$$

using a probit model, where $d_{it} = 1$ if $y_{it} > 0$ and is zero otherwise, X is vector of covariates, and β is a vector of parameters to be estimated. A second empirical approach makes use of the count nature of the infections data. We assume that the counts follow a Poisson process and model the count of infections within a 10km^2 unit directly. The Poisson count model is given by:

$$Pr(y = Y|X) = \frac{e^{-\lambda(X\beta)}\lambda(X\beta)^Y}{Y!}, \quad \text{for} \quad y = 0, 1, 2, \ldots, \tag{7}$$

where $\lambda(X\beta)$ represents the conditional mean and variance of the random variable. We relate λ to explanatory variables through a logarithmic link function. Maximum likelihood estimation procedures are used for both the probit and Poisson models.

6 Data and Empirical Results

Our empirical analysis is based upon inspections data collected under the Florida Citrus Canker Eradication Program. The inspections data span 1996 through 2004. Data describing characteristics of the multiblock units and inspections reports were obtained from the Florida Department of Agriculture and Consumer Services Division of Plant Industry. The survey data report on the results of periodic inspections, which are made an average of 1.3 times per year on each multiblock. The data consist of reports on 338,226 inspections.

6.1 Discussion of Data

Our unit of observation for our empirical analysis is the 10 km^2 unit of aggregation. The existing scientific evidence suggests that a number of observable factors may be relevant to the likelihood of infection. In particular, we know that certain fruit varieties are more susceptible to canker infection than others. Limes, lemons, and grapefruits tend to be more susceptible than oranges and tangerines. We consider four variables representing the proportions of the citrus grove acreage in each aggregate unit devoted to particular fruit types—oranges, tangerines, grapefruit, and all other fruits (which consist of limes, lemons, carambolas, and other minor fruit varieties). It is also the case that there is considerable heterogeneity across our 10 km^2 units in the amount of citrus acreage. It is certainly the case that areas with more acreage are more likely to be found with infections. This occurs for two reasons. First, the infectious nature of citrus canker suggests that a more dense concentration of citrus trees will correspond to a higher risk of infection. Second, there are likely to be more inspections in areas with more trees and thus a greater likelihood exists that canker will be found.[9] We include the total acreage of citrus surveyed in each unit as a conditioning variable in the probit and Poisson models. It is also the case that groves frequently have dormant acreage. Such dormant acreage could serve as a buffer against infection, at least to the extent that it insulates the fruit-bearing trees from the boundaries of the multiblock units. We include the proportion of total acreage that is dormant. Finally, we utilize a count of the total number of positive multiblocks found in neighboring units in the previous calendar year. Recall that neighboring units are defined as any unit whose centroid is within 30 km of the unit of interest.

We utilize two indicators of a positive infection status. The first is simply an indicator of a positive finding in an inspection. The second indicator of infection is defined by a positive finding or any inspection in the two year period following a positive finding. Regulations under the Canker Eradication Program require that any grove found to be infected with canker must have its trees destroyed and then must remain fallow for a two-year period. This requirement assumes that canker spores remain infectious for up to two years after the trees are removed. Thus, our second measure assumes that all groves remain infected over the two years that follow a positive canker finding. Our dependent variables are the sums of these positive indicators over a calendar year period.

6.2 Empirical Results

The overarching goal of our models is to provide measures of the risk of canker infection which could be applied in the construction of insurance or indemnification plans. Perhaps the most straightforward approach to measuring such risk is to examine the locations of current and past infections and use spatial smoothing techniques to extrapolate exposure frequencies to provide infection probabil-

[9] This raises an interesting point about our modeling exercise. We are not actually modeling the risk of infection but rather the risk that infection will be found by inspections. Of course, canker may exist and not be observed but such an event would not trigger indemnities under an insurance program and thus would not be relevant to the likelihood of payouts.

ity measures. Of course, such an approach ignores any of the conditioning information that, as we have discussed, may be relevant to the risk of infection. Figure 4 presents infection probabilities obtained from spatial smoothing of historical infections in the inspections data. We used simple kriging procedures to estimate the probability surface.[10] The surface indicates a higher probability of infection in the Miami area and in a few other areas that have experienced canker infections.

Such an approach ignores any conditioning information outside of historical infection locations that may be useful in assessing risks. In particular, as we have outlined in previous sections, plant pathology research has established that infection risks tend to be dependent upon a number of factors, including the type of fruit and timing of infections in neighboring groves. Thus, it is likely that risk models that use such conditioning information may be much more informative. We estimated probit models of the discrete infection status ($d_{it} = 1$ for one or more infections and is zero otherwise). Recall that we utilize two measures of infection—a positive find and a positive status (the two year period following a positive find). Table 3 presents summary statistics for measures of infection and other relevant explanatory factors. We present variable definitions and summary statistics both for the individual multiblock (grove) units and for the aggregate 10 km^2 block units in Table 3. There are 337,932 multiblock-level inspection observations and 2,380 annual aggregate block unit observations. Note that about 3.4 percent of the aggregate observations have a positive infection status while only 2.5 percent of the aggregate observations have positive finds. About 75 percent of the citrus production is oranges, with other fruits accounting for smaller proportions.

Table 4 contains parameter estimates and summary statistics for the probit models of citrus canker infections. In both the positive find and positive status models, the parameters reveal a high degree of statistical significance, indicating the high degree of relevance of the conditioning variables. A likelihood ratio test of the joint significance of all of the explanatory factors is highly significant in each case. McFadden's LRI (also known as McFadden's R^2) ranges from about 0.215 to 0.232, again confirming the high degree of significance of the probit risk models. As expected, the risk models suggest that the likelihood of canker infection varies substantially across different fruit types. In particular, the parameter estimates for the model of positive status suggest that oranges and grapefruits have the lowest rates of infection, followed next by tangerines and finally by other

[10] Kriging procedures are regression techniques used in to spatially approximate or interpolate data. They predict unknown values from data at known locations.

fruits (the default category), which consists of lemons, limes, and other minor citrus commodities. Results are very similar for the model of positive finds, with the exception that tangerines now are implied to have the lowest risks of infection, although the tangerine coefficient is not statistically different from that for oranges and grapefruit. These findings are consistent with the implications of biological research, which has suggested that lemons and limes tend to be much more susceptible to citrus canker infections. It is important to point out that ignorance of fruit type in constructing and rating an insurance or indemnity plan would result in inaccurate rates, since important information relevant to the risks of infection would be ignored.

The probit models also suggest that the total amount of citrus acreage within each block is significantly related to the likelihood that inspections will reveal citrus canker. Again, this likely reflects the higher likelihood of infection in areas with a greater density of fruit trees as well as the greater likelihood that inspections will uncover one or more infections in areas with more trees. The proportion of grove area that is dormant has a negative, though not statistically significant relationship with infection risks.

Finally, the probit models confirm suspicions that infection risk tends to be spatially and temporally related to the realizations of other infections in neighboring areas. The count of positive inspections in all neighboring units (defined by those units with centroids within 30 miles of the center of the unit) has a positive and statistically significant effect on the probability of infection. This suggests that actuarially fair premium or checkoff rates will be higher in areas in close proximity to infections in the preceding year.

Predictions from the probit models provide measures of the expected probabilities of canker infection. These probabilities are conditioned on fruit type, size, and the status of groves in neighboring blocks in the previous year. Figure 5 presents a spatially smoothed (by krigging methods) representation of the predicted probability of canker infection. In comparison to Figure 4, which ignored all conditioning variables, a much richer picture of the risks of infection is offered by the probit models. In particular, the probit model predictions recognize the fact that infection risks are dependent upon the type of fruit, the density of production, and the status of neighboring units.

The probit models provide statistically significant measures of the effects of various factors on canker infection probabilities. However, these models do not incorporate the degree of infection that may be present in the aggregate units. In particular, the probit estimates only account for the discrete status of canker infections and thus ignore the level or degree of infection. We know the number of positive inspections and multiblock units in each aggregate unit and thus a consideration of only the discrete status may ignore valuable information that could be used in modeling infection probabilities. To address this potential shortcoming, we also estimated Poisson count data regression models. The Poisson model parameter estimates and summary statistics are presented in Table 4.

The results are largely consistent with those obtained for the probit models. The estimates suggest that the risk of infection varies significantly across different fruit types, with oranges and grapefruits being the least susceptible, followed by tangerines and all other fruits. In contrast to the probit results, the share of acreage that is dormant now reflects a statistically significant negative relationship with infection risks. This is in accordance with expectations in that canker infection is expected to be less likely on dormant grove acreage. Dormant space may also serve to buffer existing fruit from future infections.

The Poisson models also confirm the probit results suggesting that infections in neighboring units raise the likelihood that an infection will occur. Again, this reflects the infectious nature of citrus canker, which can be spread across space through a multitude of transmission means. Finally, the total scale of citrus acreage is again found to be significantly related to the likelihood of canker infection. This reflects the density factors and increased inspection frequency discussed above. One version of the Poisson regression model recognizes the fact that the counts may be measured over different possible numbers of positive events (i.e., in our case, different numbers of inspections). In such a case, adjustments may be made to recognize this different "rate" of positive events. We do not pursue this estimation approach for two reasons. First, our inclusion of the total acreage as an explanatory factor explicitly accounts for differences in the rate of inspections, though in a more flexible manner than would be the case if an explicit adjustment were made to account for differing inspection rates. Second, we suspect that the density of citrus trees may have an important causal relationship with canker inspection risks and thus want to allow for a flexible relationship between the rate of inspections and the likelihood of canker infection.[11] Figure 6 presents the estimated probability of infection obtained from the Poisson model of positive infection status. Again, a much

[11] This rate adjustment, often called an "offset" adjustment, is analogous to entering the rate variable as a covariate with its parameter constrained to be one. We pursue a more flexible specification.

richer probability surface is implied by recognition of the conditioning variables.

In all, the regression models confirm contentions that citrus canker infection risks tend to vary substantially across different fruit types, with risks the highest for lemons and limes and the lowest for oranges and tangerines. Density of production and infections in neighboring areas also tend to be significantly related to infection risks.

6.3 The Preponderance of Zeros Problem

As we have noted above, infection by canker remains a relatively rare event—at least in most parts of the state. This is reflected in our data in that only a very small proportion of the inspections revealed the presence of canker. In modeling infection probabilities, we adopted two separate models. In the first, a probit model was used to model the discrete infection/no-infection probability, thus ignoring the enumerative nature of infection counts in a particular unit. In a second model, we used a Poisson distribution to capture the degree of infection represented in the counts. As is true with any parametric specification, such an approach imposes a particular distribution on the model to the parameters of interest.

Recent research has recognized the fact that many of the parametric specifications used to model count data may be inappropriate in cases where the data do not fit the underlying distribution. A particular case—and one that characterizes our data—arises when the count data reflect a preponderance of zero counts. Forcing a specific distribution to conform to actual counts that involve such a preponderance of zeros may result in important misspecifications. Figure 6 presents a histogram of our count data. The extreme preponderance of observations with zero infections is apparent. Panel (b) of Figure 6 illustrates a Poisson distribution, fit to our data (absent any conditioning on covariates). The degree of potential misspecification is apparent in the figure, where the distributional aspects of the observed count data result in a significant overstatement of the probability of small infection counts.

Various mixture models have been developed to address this misspecification issue. These models typically involve a mixture of a discrete model, representing the discrete 0/1 threshold represented above by our probit models and a model appropriate for the count data above zero. These models are commonly referred to as "zero-inflation" models. We adopted a zero-inflation Poisson model, which was defined by a mixture of a probit model to capture the discrete infection/no-infection distinction and a Poisson model to represent positive counts. This model is given by

$$\begin{aligned} Pr(Y=0) &= \phi(Z\gamma) + (1-\phi(Z\gamma))e^{-\theta(X\beta)} \\ Pr(Y=y) &= (1-\phi(Z\gamma))\frac{e^{-\theta(X\beta)}\theta(X\beta)^y}{y!}, \quad \text{for } y=1,2,\ldots, \end{aligned} \tag{8}$$

where Z represents covariates relevant to the discrete status of infection, X represents covariates relevant to the level of infection on infected units, and γ and β are parameters to be estimated. In order to simplify comparisons with the preceding probit estimates, we define $\phi = 1 - F(Z\gamma)$ against convention so that a positive event corresponds to $y > 0$.

We used maximum likelihood procedures to estimate zero-inflation mixture Poisson models of the positive canker status and positive canker inspections. The resulting estimates are presented in Table 6. This approach has the advantage of jointly modeling the infection status and the degree of infection. The selection mechanism estimates, are very similar to the analogous probit estimates presented above. In contrast, the Poisson portion of the model reveals parameter estimates that are considerably different from those that were obtained from a standard Poisson model. The same general implications for the relationships between observable unit characteristics and infection rates are represented by the zero-inflation models.

6.4 Insurance/Checkoff Premiums

The ultimate goal of our analysis is to use the estimated risk models to construct measures of actuarially-fair premiums for an insurance or indemnity fund. In the context of our analysis, the actuarially-fair premium will be set equal to expected loss, which is given by

$$E\{Loss_{iJ}\} = Pr(\text{Unit}_J\text{=Positive}|X_J) \cdot Pr(\text{multiblock}_{iJ}\text{=Positive}|Z_{iJ}) \cdot \text{Payment}, \tag{9}$$

where Unit_J represents 10 km^2 unit J having conditioning factors X_J and multiblock_{iJ} represents multiblock i in Unit J, having conditioning factors Z_{iJ}. In terms of our model parameters, expected loss can be equivalently represented by

$$E\{Loss_{iJ}\} = F_i(X\beta) \cdot G_J(Z_{iJ}\gamma) \cdot \text{Payment}, \quad \text{for} \quad i \in J. \tag{10}$$

where i corresponds to multiblock i and J corresponds to aggregate 10 km^2 Unit J. "Payment" represents the payment to be made per acre in the event of a positive canker infection. In light of the calculations presented above, we assume that a unit of citrus stock is worth approximately

\$10,000 per acre and thus set the payment at this level.[12] The probit and Poisson models yield empirical measures of risk for the aggregate unit, given by $G_J(\cdot)$. We assume that all multiblock units within an aggregate unit having a positive status face an equal probability of infection and thus use the proportion of positive multiblocks in positive units as an empirical measure of $F_i(\cdot)$. This proportion is 0.0255 for positive status and 0.0269 for positive finds.

Table 5 contains summary statistics for the estimated premiums for individual multiblocks. The premiums differ substantially across the alternative models, ranging from an average of \$6.39 per acre for the probit model of positive finds to \$38.91 for the Poisson model of positive canker status. As we have noted, the Poisson models may be suspect in light of the relatively rare nature of canker infections (less than 5 percent). The zero-inflation Poisson models produce premiums that are very similar to those implied by the standard probit model.

Finally, it is possible that one may wish to further refine rates to reflect information about the makeup of individual multiblocks. In particular, one may want to lift our assumption that $G_J(\cdot)$ is fixed across all individuals in a multiblock and instead allow it to vary according to multiblock characteristics. As we have noted above, at least in the case of our aggregate units, the type of fruit and size of the area under consideration may be relevant to infection probabilities. Of course, insurers must weigh the utility of individual rate refinements against the programmatic shortcomings associated with premium rates that vary substantially across neighboring individuals. We estimated standard probit models of infection rates and status for the subsample of multiblocks within units having a positive infection status or find. The resulting parameter estimates are presented in Table 8. These estimates demonstrate that further rate refinements may be possible by accounting for factors specific to an individual multiblock unit. In particular, the probit estimates suggest that, within aggregate units having a positive infection status, groves with tangerines are the least likely to realize infection, followed by oranges and then by grapefruits. The highest rates of infection are again implied for the miscellaneous fruits, including lemons and limes. Again, infection probablities are shown to vary directly with the size of the groves and intensity of inspections.

[12]The basis for this value of \$10,000 per acre was formulated from the value of lost production and tree replacement, as is shown in Table 1. Note that, as long as risk is not endogenous to the payment level, risk and the underlying premium rate is transparent to the assumed payment level. Of course, a payment rate that is set too high may provide incentives for individuals to undertake actions that could increase their likelihood of collecting indemnities—the case of moral hazard.

7 Concluding Remarks

This analysis presents and evaluates models of the infection risks associated with Asiatic Citrus Canker in Florida citrus. We provide an overview of the history of citrus canker outbreaks in Florida. We also review biological aspects of citrus canker and discuss its relevance within the wider framework of invasive species impacts on agriculture. We discuss methodological issues associated with the design of insurance and/or indemnification plan programs that would provide a form of "self-help" risk protection for Florida citrus producers. The plan is presented in the form of a specific-peril program that offers to indemnify only those damages associated with citrus canker infections. The overarching goal of our analysis is to construct empirical risk models that allow us to quantify the risks of canker infection and uses these measures to identify actuarially-fair premiums or check-off charges that should be paid for this protection.

We estimate probit and Poisson regression models that relate the risk of canker infection to a number of conditioning variables. Our models reveal that the risks of infection varies substantially across different types of fruit. The risk is lowest for oranges, followed then by tangerines and grapefruits. Minor citrus commodities, including limes and lemons, are found to face the highest risk of infection with canker. Our empirical models also reveal important spatio-temporal aspects of infection. Canker infection in neighboring regions significantly raises the likelihood of infection. The size and density of citrus production in an area is positively related to the likelihood that canker infections will be found. The probit and Poisson model estimates are used to rate insurance/indemnity fund plans. Rates varied from \$6.39 per acre to \$38.91 per acre, with our preferred model estimating rates to be \$8.16 per acre for positive finds and \$8.36 per acre for positive status. Furthermore, the models suggest that the risks and thus premiums for protection are highest in the southern regions of Florida. This area is notable in that it has realized the highest incidence of canker infection.

A number of extensions to this research are currently being investigated. In particular, several hurricane events that were realized in 2004 are very likely to be relevant to infections in 2005. Our analysis did not include data for the 2005 calendar year as our analysis utilizes data collected through mid-2005. As additional data are made available, we will focus modeling efforts on capturing the effects of the 2004 hurricanes, which are believed to have dispersed canker spores and thus led to a substantial increase in infections in 2005.

Table 1. Lost Production Payment and Tree Replacement by Variety

Citrus Varieties	Lost Prod.[a] Payment[a] (a)	Max. Tree[b] Replacement[b] (b)	Combined (a) + (b)
		Dollars Per Acre	
Limes	6,503	4,004	10,507
Orange, valencia, and tangerine	6,446	3,198	9,644
Orange, navel*	6,384	3,068	9,452
Grapefruit	3,342	2,704	6,046
Other mixed citrus	3,342	2,704	6,046
Tangelos	1,989	2,964	4,953

*Source: USDA-APHIS (2002); USDA-APHIS (2000), includes early and midseason oranges.

[a]Per acre loss in the net present value; Tree replacement cost has been deducted; Per-acre income is determined by yield per tree (# boxes) multiplied by the price of a box less production costs per tree; the cash flow per tree is multiplied by the number of trees to determine per-acre net income.

[b]Based on up to a $26 per tree allowance; Per acre caps were calculated by $26 times the varietal average number of trees per acre; The $26 per tree allowance covers land preparation, replacement tree, labor for planting, and maintenance until the tree become productive.

Table 2. Florida Fruit Tree Crop Insurance Liabilities by Type and Mode of Delivery 1999-2005

Tree Type	RBUP (a)	CAT (b)	Total (a)+(b)	%RBUP	%CAT	Loss Ratio *RBUP*	Loss Ratio *CAT*
		dollars					
		1999					
All Other	2, 811, 985	10, 310, 390	13, 122, 375	21.4%	78.6%	0.00	0.00
Carambola	23, 071	328, 662	351, 733	6.6%	93.4%	0.00	0.00
Grapefruit	2, 805, 598	7, 557, 637	10, 363, 235	27.1%	72.9%	0.00	0.00
Lemon	0	0	0	0.0%	0.0%	0.00	0.00
Lime	458, 456	2, 577, 002	3, 035, 458	15.1%	84.9%	0.00	0.00
Orange	7, 962, 313	121, 946, 556	129, 908, 869	6.1%	93.9%	0.00	0.00
Totals	14, 061, 423	142, 720, 247	156, 781, 670	9.0%	91.0%		0.00
		2000					
All Other	15, 443, 152	28, 301, 459	43, 744, 611	35.3%	64.7%	0.00	0.01
Carambola	24, 042	356, 282	380, 324	6.3%	93.7%	0.00	0.00
Grapefruit	56, 248, 255	45, 846, 180	102, 094, 435	55.1%	44.9%	0.38	0.79
Lemon	7, 905	921, 521	929, 426	0.9%	99.1%	0.00	0.00
Lime	6, 411, 535	440, 557	6, 852, 092	93.6%	6.4%	14.23	11.70
Orange	143, 406, 947	399, 847, 231	543, 254, 178	26.4%	73.6%	0.10	0.15
Totals	221, 541, 836	475, 713, 230	697, 255, 066	31.8%	68.2%		0.46
		2001					
All Other	25, 226, 259	19, 830, 179	45, 056, 438	56.0%	44.0%	0.02	0.09
Carambola	67, 320	174, 723	242, 043	27.8%	72.2%	2.06	0
Grapefruit	70, 736, 716	39, 795, 419	110, 532, 135	64.0%	36.0%	0.12	0.05
Lemon	1, 689, 194	0	1, 689, 194	100.0%	0.0%	0	0
Lime	4, 072, 664	63, 959	4, 136, 623	98.5%	1.5%	4.38	0
Orange	319, 596, 759	349, 139, 103	668, 735, 862	47.8%	52.2%	0.21	0.14
Totals	421, 388, 912	409, 003, 383	830, 392, 295	50.7%	49.3%		0.19

Source: Federal Crop Insurance Corporation (http://www3.rma.usda.gov/apps/sob/)

Table 2. (continued)

Tree Type	RBUP (a)	CAT (b)	Total (a)+(b)	%RBUP	%CAT	Loss Ratio *RBUP*	Loss Ratio *CAT*
		dollars					
		2002					
All Other	35,503,321	20,725,293	56,228,614	63.1%	36.9%	0.00	0.00
Carambola	66,258	177,610	243,868	27.2%	72.8%	0.00	0.00
Grapefruit	88,630,388	41,334,491	129,964,879	68.2%	31.8%	0.00	0.07
Lemon	1,956,975	0	1,956,975	100.0%	0.0%	0.00	0.00
Lime	2,955,168	55,863	3,011,031	98.1%	1.9%	12.85	0.00
Orange	550,896,566	349,986,384	900,882,950	61.2%	38.8%	0.02	0.15
Totals	680,008,676	412,279,641	1,092,288,317	62.3%	37.7%		0.10
		2003					
All Other	32,902,961	19,106,230	52,009,191	63.3%	36.7%	0.10	0.03
Carambola	63,347	138,160	201,507	31.4%	68.6%	0.00	0.00
Grapefruit	81,166,014	35,757,250	116,923,264	69.4%	30.6%	0.26	0.07
Lemon	2,061,634	0	2,061,634	100.0%	0.0%	0.00	0.00
Lime	1,117,735	223,463	1,341,198	83.3%	16.7%	6.63	4.41
Orange	578,491,191	299,200,543	877,691,734	65.9%	34.1%	0.06	0.19
Totals	695,802,882	354,425,646	1,050,228,528	66.3%	33.7%		0.12
		2004					
All Other	30,100,685	19,560,289	49,660,974	60.6%	39.4%	0.49	0.09
Carambola	51,644	138,160	189,804	27.2%	72.8%	0.00	0.00
Grapefruit	77,462,930	40,678,332	118,141,262	65.6%	34.4%	0.55	0.01
Lemon	1,956,975	0	1,956,975	100.0%	0.0%	0.00	0.00
Lime	694,339	165,539	859,878	80.7%	19.3%	0.00	0.00
Orange	445,408,732	399,413,843	844,822,575	52.7%	47.3%	0.50	0.18
Totals	555,675,305	459,956,163	1,015,631,468	54.7%	45.3%		0.36
		2005					
All Other	37,987,207	17,763,543	55,750,750	68.1%	31.9%	1.21	0.20
Carambola	50,663	141,721	192,384	26.3%	73.7%	0.00	0.00
Grapefruit	92,406,857	33,973,728	126,380,585	73.1%	26.9%	2.21	2.37
Lemon	2,022,209	0	2,022,209	100.0%	0.0%	0.00	0.00
Lime	83,012	0	83,012	100.0%	0.0%	0.00	0.00
Orange	591,502,061	366,019,094	957,521,155	61.8%	38.2%	0.81	0.88
Totals	724,052,009	417,898,086	1,141,950,095	63.4%	36.6%		1.02

Source: Federal Crop Insurance Corporation (http://www3.rma.usda.gov/apps/sob/)

Table 3. Variable Definitions and Summary Statistics

Variable	Definition	Mean	Std. Dev.
Positive Status	0/1 Indicator of a positive multiblock (up to 2 years after inspection)	0.0018	0.0419
Positive Find	0/1 Indicator of positive canker survey	0.0006	0.0241
Acres	Size of multiblock unit (acres)	16.0347	23.9317
Orange Acres	Orange acreage	13.0339	23.6261
Grapefruit Acres	Grapefruit acreage	2.0410	8.4120
Tangerine Acres	Tangerine acreage	0.5096	4.1285
Other Acres	Other fruit acreage	0.0955	1.2898
Tangelo Acres	Tangelo acreage	0.1918	2.1398
Lemon Acres	Lemon acreage	0.0634	1.0315
Lime Acres	Lime acreage	0.0986	1.4669
Dormant Land	Dormant area (thousand square meters)	4.5286	26.5660
Land Area	Total multiblock area (thousand square meters)	75.3921	107.3003
Unknown Acres	Unknown acreage	0.0010	0.1081
Orange Share	Orange acreage share	0.6885	0.4631
Grapefruit Share	Grapefruit acreage share	0.1299	0.3362
Tangerine Share	Tangerine acreage share	0.0395	0.1949
Other Share	Other fruit acreage share	0.0144	0.1192
Tangelo Share	Tangelo acreage share	0.0202	0.1406
Lemon Share	Lemon acreage share	0.0103	0.1007
Lime Share	Lime acreage share	0.0108	0.1034
Unknown Share	Unknown acreage share	0.0001	0.0109
Dormant Share	Dormant acreage share	0.0875	0.2825
$10km^2$ Unit Aggregates			
Positive Status	0/1 Indicator of a positive multiblock (up to 2 years after inspection)	0.0339	0.1810
Positive Find	0/1 Indicator of positive canker survey	0.0249	0.1558
Positive Status Count	Count of positive status multiblocks	0.2386	1.9146
Positive Find Count	Count of positive canker surveys	0.0777	0.8086
Orange Share	Orange acreage share	0.7557	0.2913
Grapefruit Share	Grapefruit acreage share	0.0903	0.1681
Tangerine Share	Tangerine acreage share	0.0536	0.1259
Dormant Share	Dormant acreage share	0.1058	0.2115
Positive Neighbors (t-1)	Positive inspections within 30km radius in preceding year	2.2953	3.4566
Total Acreage	Total Unit Acreage (hundred thousand acres)	0.0227	0.0415

[a] Numbers of observations are 337,932 for multiblock units and 2,380 for $10km^2$ units.

Table 4. Probit Model Estimates of Canker Infection Probabilities[a]

Parameter	Estimate	Standard Error	t-Ratio
...............................Model of Positive Status			
Intercept	−1.1276	0.1737	−6.49*
Orange Share	−1.4412	0.1895	−7.60*
Grapefruit Share	−1.4452	0.3705	−3.90*
Tangerine Share	−0.5723	0.4170	−1.37
Dormant Share	−0.2442	0.2559	−0.95
Positive Neighbors (t-1)	0.0298	0.0153	1.94*
Total Acreage	9.7497	0.9018	10.81*
Likelihood Ratio Test	160.67*		
McFadden's LRI	0.2320*		
...............................Model of Positive Finds			
Intercept	−1.1792	0.1799	−6.55*
Orange Share	−1.4538	0.1976	−7.36*
Grapefruit Share	−1.4180	0.3973	−3.57*
Tangerine Share	−1.6328	0.8252	−1.98*
Dormant Share	−0.2909	0.2695	−1.08
Positive Neighbors (t-1)	0.0438	0.0164	2.67*
Total Acreage	7.7047	0.9188	8.39*
Likelihood Ratio Test	116.90*		
McFadden's LRI	0.2150*		

[a] Asterisks indicate statistical significance at the $\alpha = .10$ or smaller level.

Table 5. Poisson Model Estimates of Canker Infection Counts[a]

Parameter	Estimate	Standard Error	t-Ratio
..........................Poisson Model of Positive Status	....		
Intercept	−0.4955	0.1292	−3.84*
Orange Share	−2.1103	0.1406	−15.01*
Grapefruit Share	−3.3933	0.3564	−9.52*
Tangerine Share	−1.1824	0.3860	−3.06*
Dormant Share	−0.6042	0.2088	−2.89*
Positive Neighbors (t-1)	0.0923	0.0104	8.88*
Total Acreage	12.8483	0.2782	46.18*
Pearson's χ^2	13,955.13*		
..........................Poisson Model of Positive Finds	....		
Intercept	−0.4877	0.1535	−3.18*
Orange Share	−3.6224	0.2093	−17.31*
Grapefruit Share	−3.5553	0.5393	−6.59*
Tangerine Share	−2.9416	0.8686	−3.39*
Dormant Share	−1.3216	0.2931	−4.51*
Positive Neighbors (t-1)	0.0851	0.0179	4.75*
Total Acreage	11.9731	0.6554	18.27*
Pearson's χ^2	7,373.91*		

[a] Asterisks indicate statistical significance at the $\alpha = .10$ or smaller level.

Table 6. Zero-Inflation Poisson Models

	Probit Selection Mechanism			Positive Counts		
Parameter	Estimate	Standard Error	t-Ratio	Estimate	Standard Error	t-Ratio
..... Model of Positive Status						
Intercept	−1.1174	0.1759	−6.35*	1.3667	0.1403	9.74*
Orange Share	−1.4522	0.1920	−7.56*	0.2850	0.1469	1.94*
Grapefruit Share	−1.3987	0.3785	−3.70*	−1.3757	0.4434	−3.10*
Tangerine Share	−0.5263	0.4325	−1.22	−0.6770	0.6002	−1.13
Dormant Share	−0.2432	0.2586	−0.94	−0.0053	0.3624	−0.01
Positive Neighbors (t-1)	0.0291	0.0154	1.89*	0.0319	0.0123	2.60*
Total Acreage	9.7252	0.8730	11.14*	3.8827	0.4633	8.38*
..... Model of Positive Finds						
Intercept	−1.1775	0.1875	−6.28*	1.3651	0.2547	5.36*
Orange Share	−1.2221	0.2234	−5.47*	−1.7287	0.3387	−5.10*
Grapefruit Share	−1.1423	0.4970	−2.30*	−2.1370	0.9511	−2.25*
Tangerine Share	−1.7750	0.9218	−1.93*	0.1754	2.1709	0.08
Dormant Share	−0.3725	0.2828	−1.32	1.0804	0.6798	1.59
Positive Neighbors (t-1)	0.0548	0.0185	2.96*	−0.0386	0.0255	−1.51
Total Acreage	6.6719	1.0548	6.33*	8.5179	2.5036	3.40*

[a] Asterisks indicate statistical significance at the $\alpha = .10$ or smaller level.

Table 7. Summary Statistics on Premiums ($/acre) for Canker Coverage

Model	Mean	Standard Deviation	Min	Max
Probit Model on Positives	8.04	13.15	0.89	146.56
Probit Model on Positive Finds	6.39	10.74	0.55	109.17
Poisson Model on Positives	38.91	30.16	6.22	221.63
Poisson Model on Positive Finds	16.15	27.46	1.99	172.98
Zero-Inflation Poisson Model on Positives	8.16	13.23	0.89	145.89
Zero-Inflation Poisson Model on Positive Finds	8.36	10.76	0.34	106.47

Table 8. Probit Model Estimates of Conditional Probabilities at Multiblock Level[a]

Parameter	Estimate	Standard Error	t-Ratio
................................Model of Positive Status			
Intercept	−1.4099	0.0424	−33.28*
Orange Share	−1.1588	0.0604	−19.18*
Grapefruit Share	−0.5873	0.0571	−10.28*
Tangerine Share	−1.5555	0.2755	−5.65*
Dormant Share	−0.2764	0.0566	−4.88*
Total Acreage	0.0019	0.0002	11.60*
Likelihood Ratio Test	514.08*		
McFadden's LRI	0.1053*		
................................Model of Positive Finds			
Intercept	−1.5402	0.0590	−26.10*
Orange Share	−1.0174	0.0942	−10.80*
Grapefruit Share	−0.4977	0.0976	−5.10*
Tangerine Share	−1.2292	0.3739	−3.29*
Dormant Share	−0.0189	0.0861	−0.22
Total Acreage	0.0012	0.0003	4.65*
Likelihood Ratio Test	173.50*		
McFadden's LRI	0.0982*		

[a] Asterisks indicate statistical significance at the $\alpha = .10$ or smaller level.

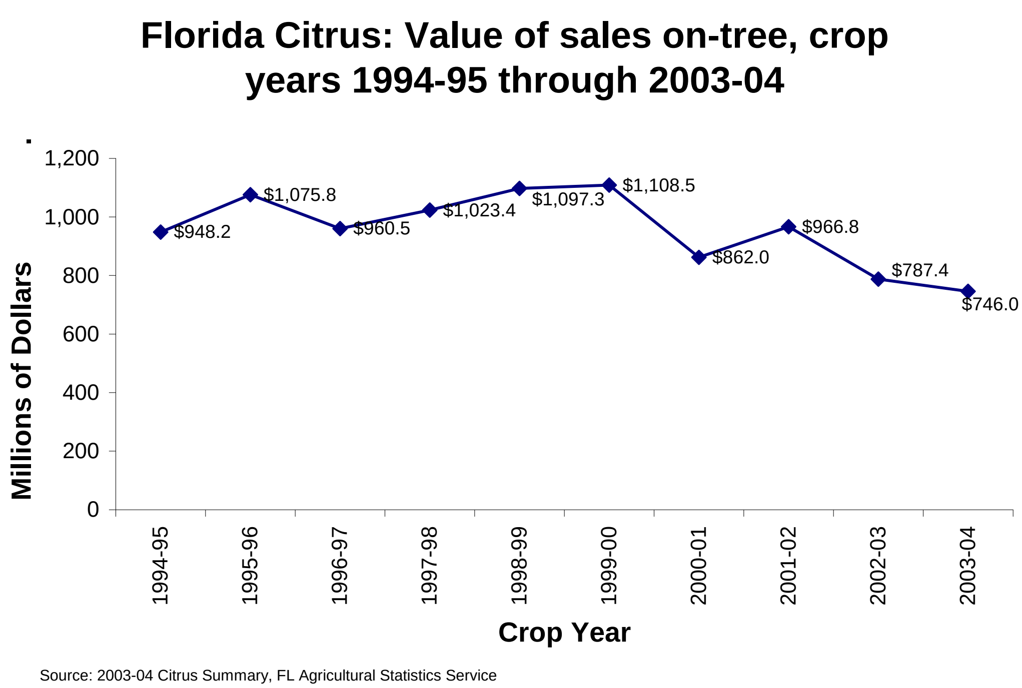


Figure 1: Florida Citrus Sales

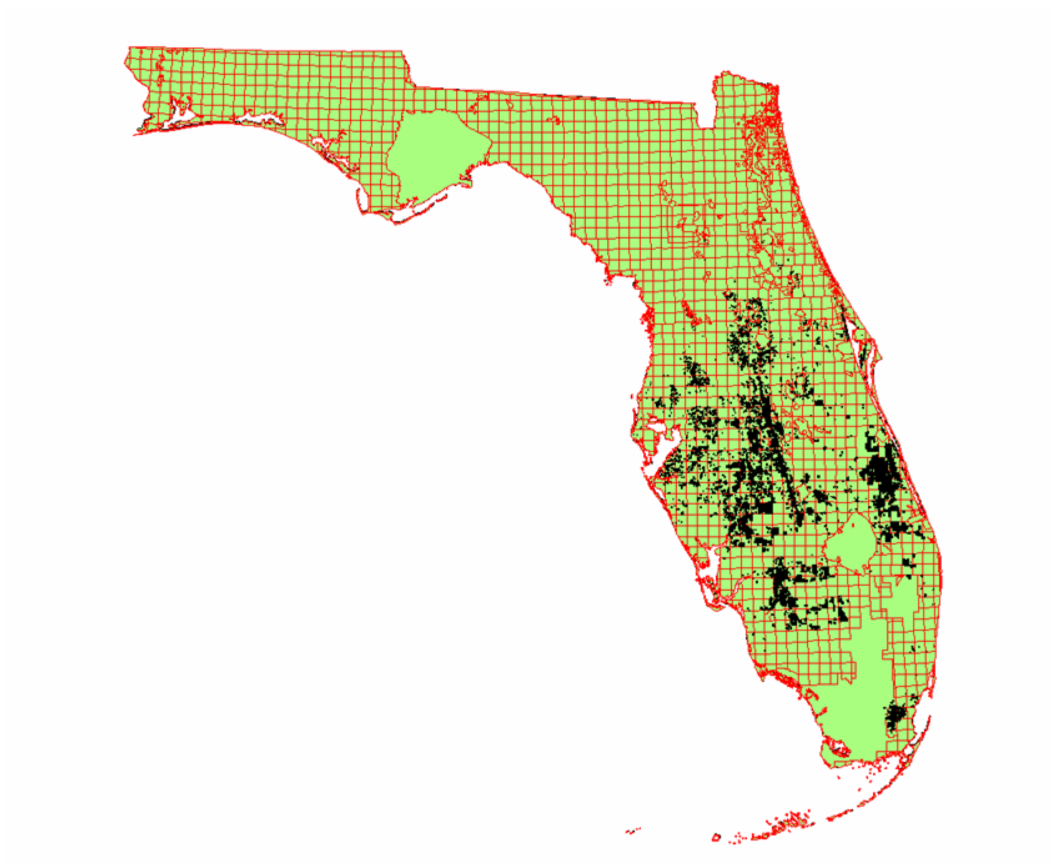


Figure 2: Multiblocks and TRS Designations

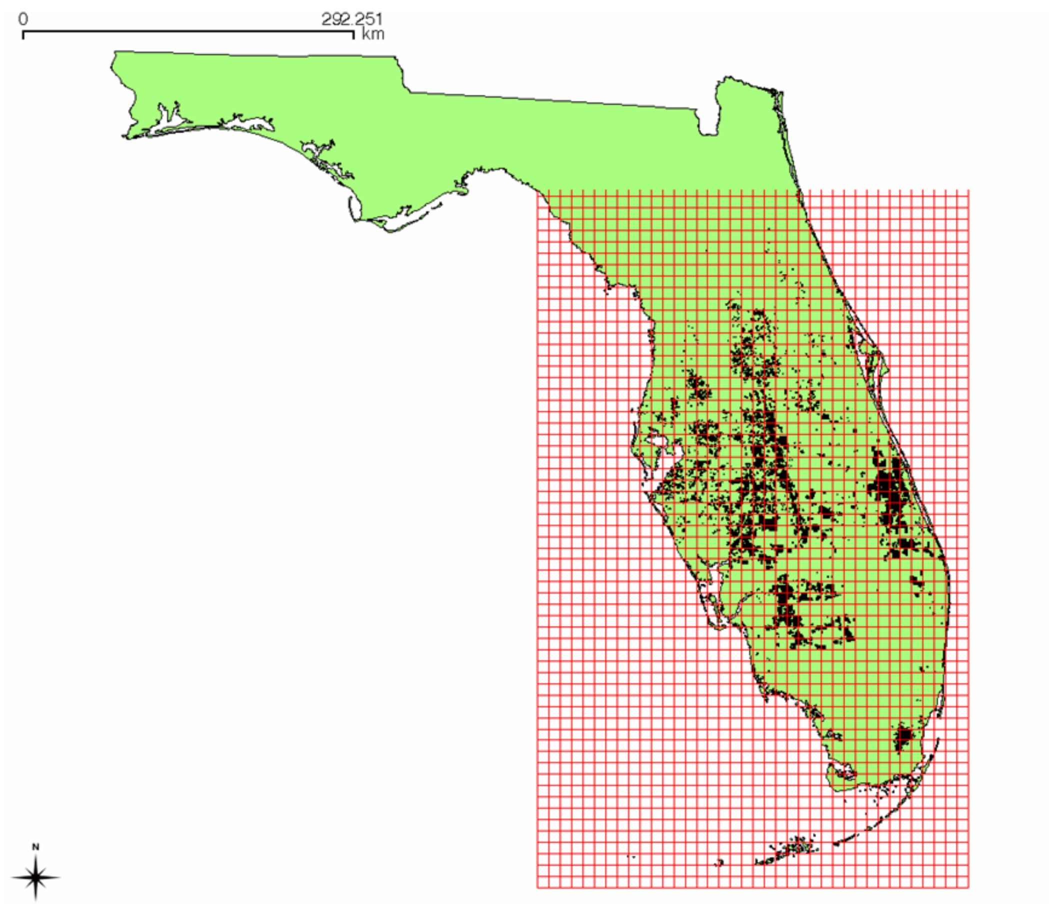


Figure 3: Multiblocks and $10km^2$ Unit Grid

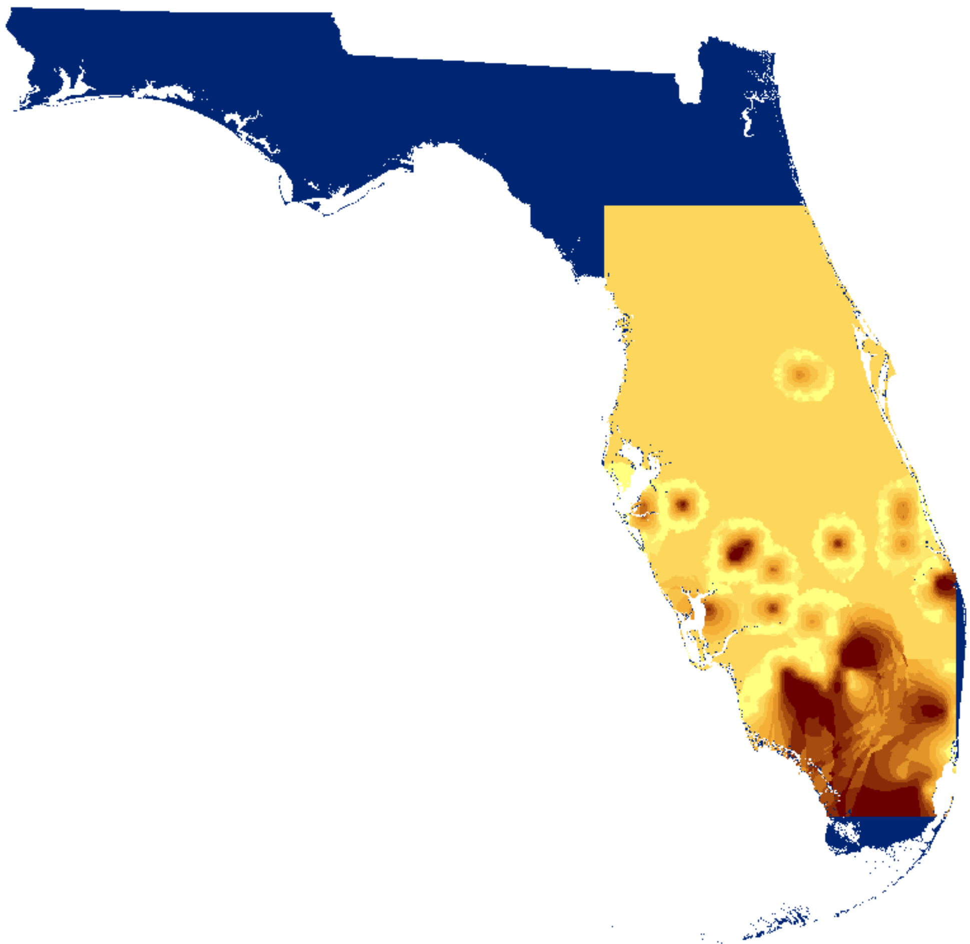


Figure 4: Predicted Probability Surface Using Actual Infection Counts

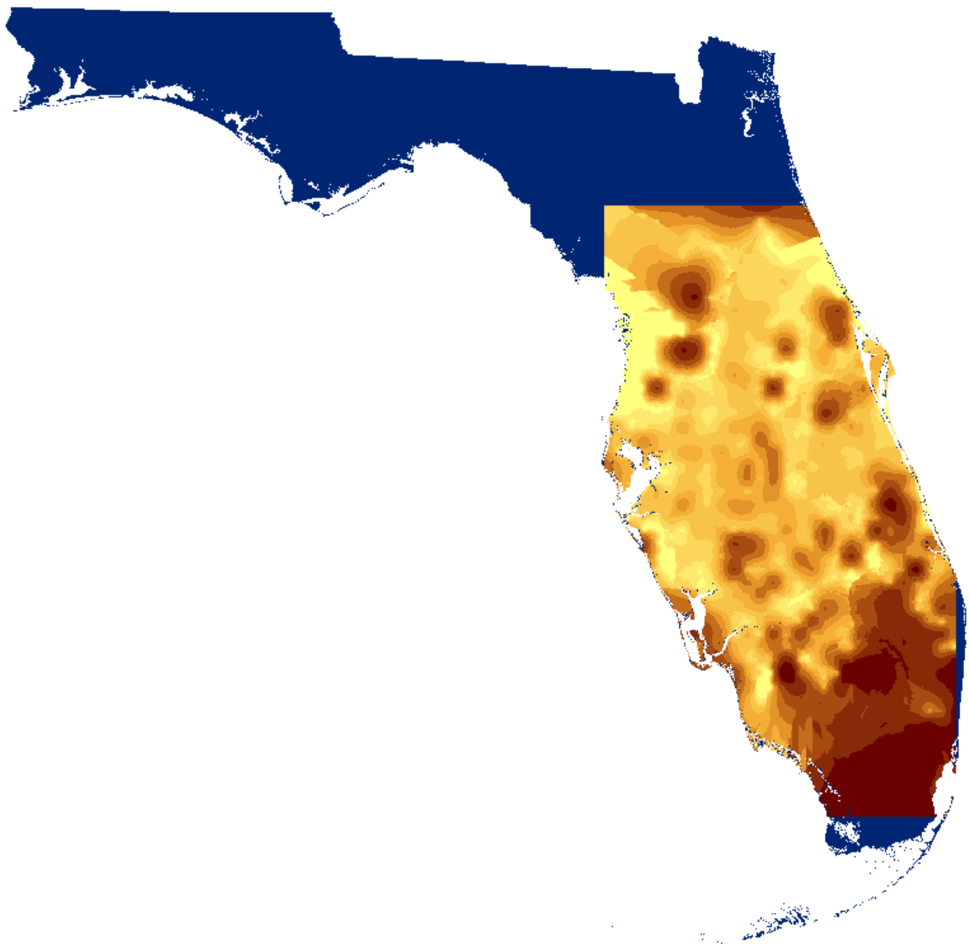


Figure 5: Predicted Probability Surface Using Probit Model

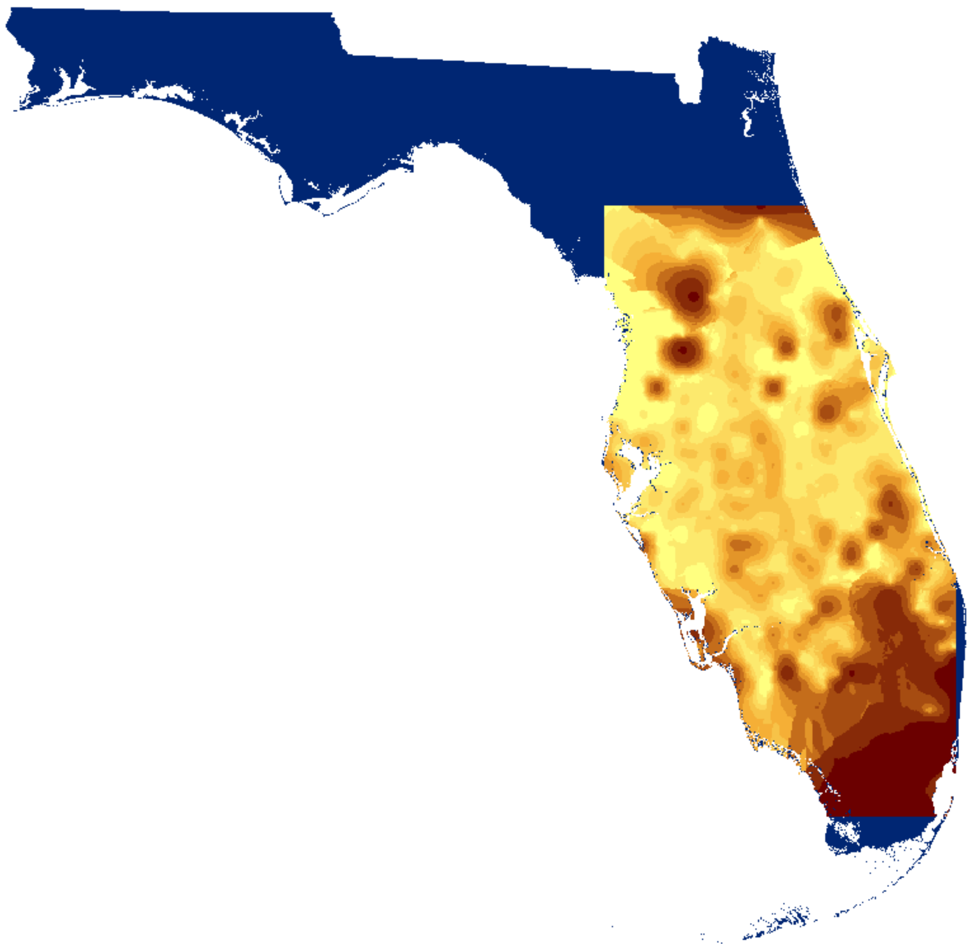
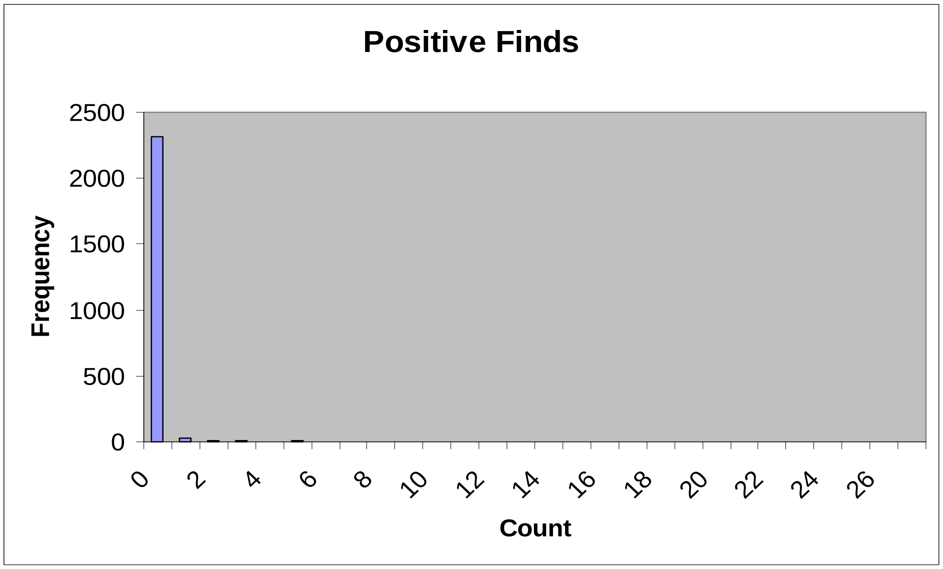
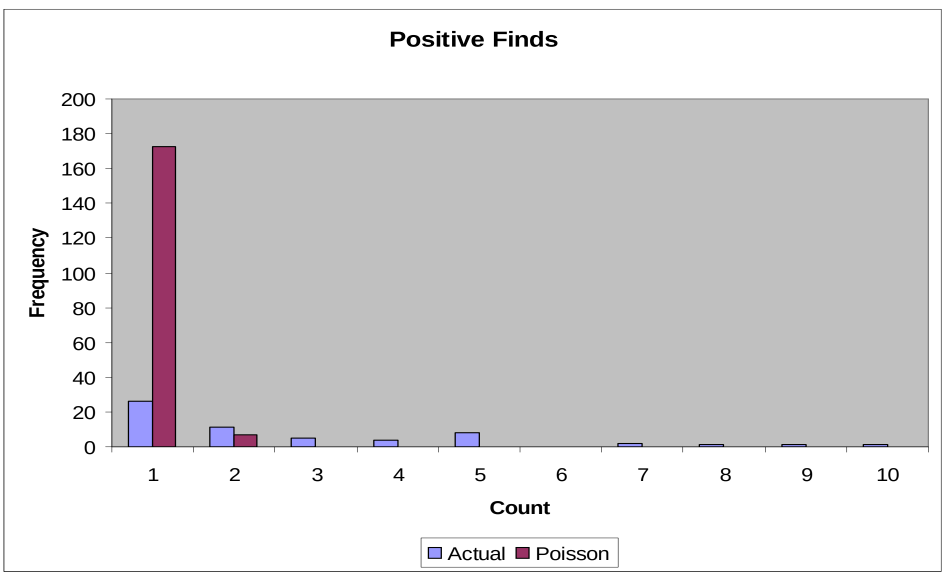


Figure 6: Predicted Probability Surface Using Poisson Model



(a) Count Frequencies



(b) Count Frequencies and Poisson Distribution

Figure 7: The Preponderance of Zeros Problem

References

Alexander, F. E., R. A. Cartwright, and P.M. McKinney (1988) 'A comparison of recent statistical techniques of testing for spatial clustering: Preliminary results.' In *Methodology of Enquiries into Disease Clustering,* ed. P. Elliott (London School of Hygiene and Tropical Medicine) pp. 23–33

Bock, C. H., P.E. Parker, and T.R. Gottwald (2005) 'Effect of simulated wind-driven rain on duration and distance of dispersal of xanthomonas axonopodis pv. citri from canker-infected citrus trees.' *Plant Disease* pp. 71–80

Florida Agricultural Statistics (2005) 'Citrus summary 2003-04.' Florida Department of Agriculture and Consumer Services. Tallahassee, FL

Goodwin, Barry K., and Vincent H. Smith (1996) *The Economics of Crop Insurance and Disaster Aid* (Washington, DC: AEI Press)

Goodwin, B.K., and A.P. Ker (2001) 'Modeling price and yield risk.' In *A Comprehensive Assessment of the Role of Risk in US Agriculture,* ed. Richard E. Just and Rulon D. Pope (Norwell, MA: Kluwer Academic Publishers) pp. 289–324

Gottwald, T. R., and L.W. Timmer (1995) 'The efficacy of windbreaks in reducing the spread of citrus canker caused by xanthomonas campestris pv citri.' *Tropical Agriculture* pp. 194–201

Gottwald, T. R., G. Hughes, J.H. Graham, X. Sun, and T. Riley (2001) 'The citrus canker epidemic in florida: The scientific basis of regulatory eradication policy for an invasive species.' *Phytopathology* 91, 30–34

Gottwald, T. R., J.H. Graham, and T.S. Schubert (1997) 'An epidemiological analysis of the spread of citrus canker in urban miami, florida, and synergistic interaction with the asian leafminer.' *Fruits* 52, 383–390

Gottwald, T. R., K.M. Reynolds, C. L. Campbell, and L.W. Timmer (1992) 'Spatial and spatiotemporal autocorrelation analysis of citrus canker epidemics in citrus nurseries and groves in argentina.' *Phytopathology* 82, 843–851

Gottwald, T. R., X. Sun, T. Riley, J.H. Graham, F. Ferrandino, and E.L. Taylor (2002) 'Georeferenced spatiotemporal analysis of the urban citrus canker epidemic in florida.' *Phytopathology* pp. 361–377

Graham, J. H., T.R. Gottwald, J. Cubero, and D.S. Achor (2004) 'Xanthomonas axonopodis pv. citri: factors affecting successful eradication of citrus canker.' *Molecular Plant Pathology* pp. 1–15

Rothenberg, R.B., and S. B. Thacker (1992) 'Guidelines for the investigation of clusters of adverse health events.' In *Geographical and Environmental Epidemiology: Methods for Small Area Studies,* ed. P. Elliott, P. Cuzick, D. English, and R. Stern (London: Oxford University Press)

Schubert, T.S., T.R. Gottwald, S.A Rizvi, J.H. Graham, X.S. Sun, and W.N Dixon (2001) 'Meeting the challenge of eradicating citrus canker in florida–again.' *Plant Disease*

USDA-APHIS (2000) 'Qs and As about citrus canker lost production payments.' Plant Protection and Quarantine Fact Sheet

——— (2002) 'Qs and As about citrus canker tree replacement.' Plant Protection and Quarantine Fact Sheet

——— (2005a) 'Citrus canker: Background.' `http://www.aphis.usda.gov/ppq/ep/citruscanker/background.html`

——— (2005b) 'Citrus canker: Chronology.' `http://www.aphis.usda.gov/ppq/ep/citruscanker/chronology.html`

USDA-RMA (2005) 'Fruit tree (pilot) florida.' 2005 Commodity Insurance Fact Sheet

Verniere, C.J., T.R. Gottwald, and O. Provost (2003) 'Disease development and symptom expression of xanthomonas axonopodis pv. citri in various citrus plant tissues.' *Phytopathology* 93, 832–843