CHAPTER 6

RISK AND INDEMNIFICATION MODELS OF INFECTIOUS PLANT DISEASES

The case of Asiatic citrus canker in Florida[*]

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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 models of the risks of citrus canker transmission. The State of Florida currently has an active inspection program that checks every commercial grove several times each year. We use data from over 338,000 inspections over the 1998-2004 period. Simple models describing 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.
Keywords: citrus canker; spatio-temporal risks; insurance models

INTRODUCTION

Florida had 748,555 acres of commercial groves in 2004 with the value of sales on-tree an estimated US$745.963 million (Florida Agricultural Statistics Service 2005). Florida is the largest citrus-growing state and accounts for 79 % of total U.S. citrus production. Figure 1 indicates that the estimated value of citrus production in Florida was $746 million in 2004, which represents a 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 amounts 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 Service 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 et al. 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

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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).

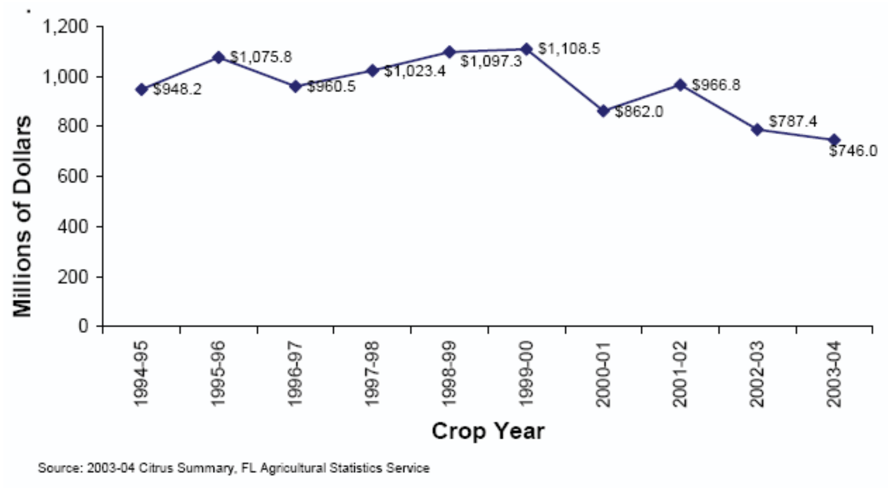

Figure 1*. Florida citrus: value of sales on-tree, crop years 1994-1995 through 2003-2004*

The current eradication program in Florida began in 1995 and has evolved into a program which involves separate infestations and different strains. It currently spans 13 Florida counties. In 1995 this current eradication program began to combat an Asiatic strain of citrus canker that was discovered in Florida in 1995 in a residential area near Miami International Airport[1]. 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 the 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, make 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).

THE HISTORY OF CITRUS CANKER OUTBREAKS

Gottwald et al. (2001) point out that 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 re-emergence 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, at present 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 U.S. Department of Agriculture (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 that 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 interims 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 1900-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 1900 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 that was signed by the Governor of Florida, authorizing the removal of all citrus trees with the 1,900-feet area and permitting the use of blank search warrants. The Department of Agriculture and Consumer Services appealed the judgment in April 2002. In May 2002, a Broward County Circuit Court judge ruled that the eradication program that 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 been 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. The first few months of 2003 saw more legal disputes which ultimately culminated with the Florida Supreme Court agreeing to hear an appeal from South Florida homeowners.

CITRUS CANKER PROGRAMS

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 USDA's Risk Management Agency (RMA) and took into consideration the costs of land preparation, replacement trees, labour 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

Table 1*. Lost-production payment and tree replacement by variety*

Citrus varieties	Lost-production [a] payment[a] (*a*)	Maximum 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, labour for planting, and maintenance until the tree become productive.

having been destroyed. However, the actual cost is estimated to be less because of the per-acre cap on payments.

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 are 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. Grapefruit 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 %.

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[2]. 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 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 that is important to our empirical modelling 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[3]. 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

***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 (cont.)

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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

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 modelling the spatial and temporal risks of transmission.

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 that 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. A large number of these papers can be characterized as investigating a within-grove (or nursery) spread as opposed to spread across fields. The results of this research are useful in that they help to ascertain how the disease is spread. However, they are not directly applicable to our modelling 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 modelling in later sections of the chapter.

Graham et al. (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[4]. 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 et al. (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.

Vernière et al. (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.

Gottwald et al. (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 et al. (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 non-contiguous elements indicated the formation of secondary foci. Further these non-contiguous elements remained until the last few assessments, made every 21 days, before they eroded and the proximity patterns generally became larger and contiguous.

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 modelling draws from distributions of yields in neighbouring geographic regions, it is clear that yield realizations from one region are certainly expected to be highly correlated with those in neighbouring areas. Spatial statistics play an important role in modelling the epidemiology of infectious diseases. An extensive literature, summarized by Alexander et al. (1988) and Rothenberg and Thacker (1992), has investigated spatial aspects of disease transmission. It is common in modelling 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 modelling 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 et al. (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 kilometres (3 kilometres north to south and 4 kilometres east to west).

This current outbreak of citrus canker presents an ideal case study for modelling risk since extensive data relating to transmission and the factors underlying risks have been collected. We shall utilize these data in an empirical model that identifies risks, potential losses, and appropriate premiums and contribution rates for an indemnification program. The State of Florida currently has an active inspection program that checks 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. Simple models describing 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.

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[5].

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 modelling 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)[6]. In the case of an indemnification fund which could be funded by a levy 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 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:

$$P \cdot max\{0, \lambda\mu - y\}. \quad (1)$$

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[7]. In this case,

$$E(Losses) = Pr(y < \lambda\mu)E(y \mid y < \lambda\mu), \quad (2)$$

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:

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

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 $\lambda\mu$:

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

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 a 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-modelling problems. A number of important questions pertain to the density function *f(y)*. A specific choice of the density function must be made. Goodwin and Ker (2002) discuss specification issues related to the distributional assumptions that must be made in modelling 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 modelling 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 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 covered 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 risk models. 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. 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 questionable.

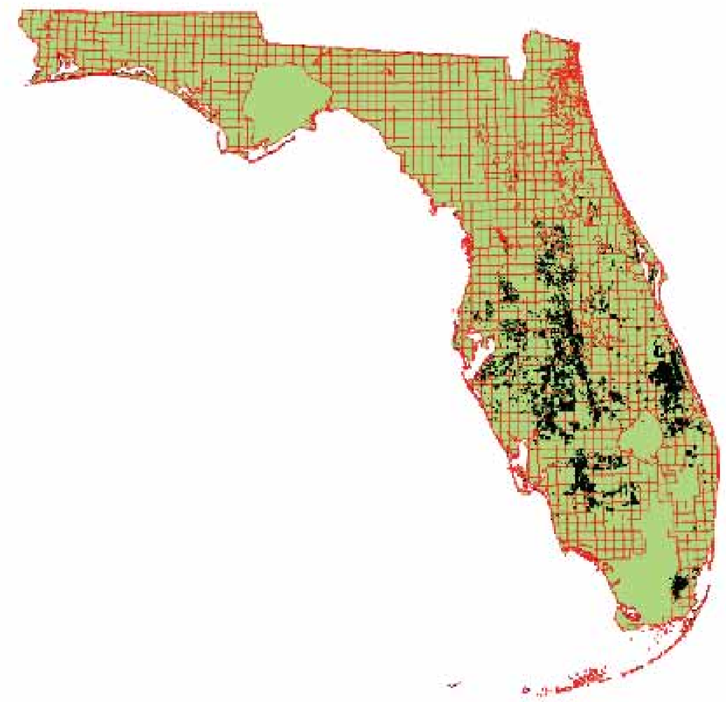

***Figure 2**. Multiblocks and TRS designations*

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 10-km^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 that 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 agent. 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].

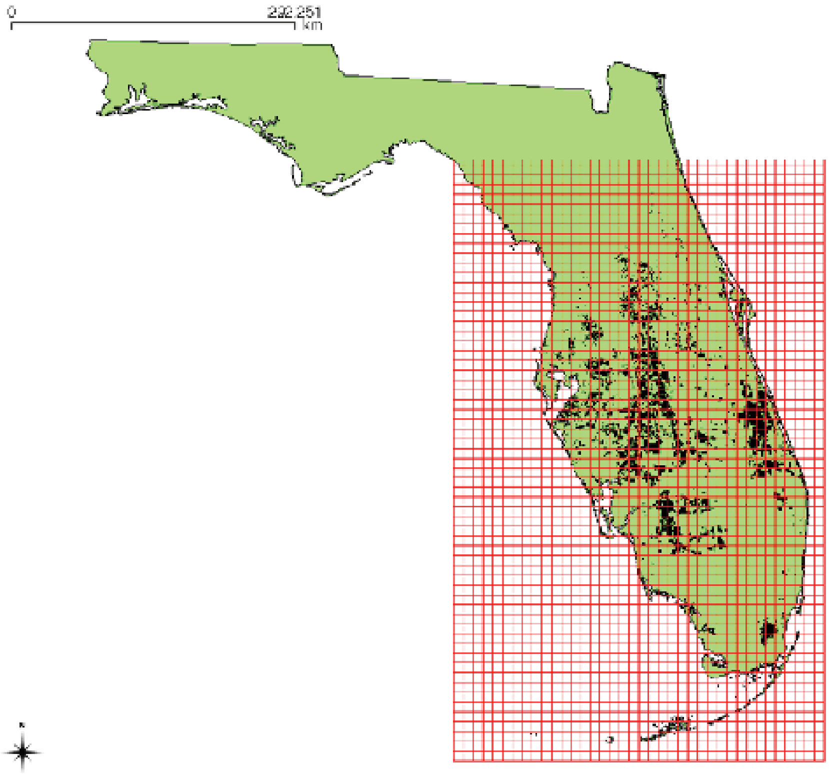

Figure 3*. Multiblocks and 10-km^2 unit grid*

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

$$Pr(y_{it}) = f(y_{it} \mid y_{jt-1},\ldots,y_{kt-1},Z_{it}) + \in_{it}, \quad (5)$$

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 neighbouring unit *j* in year *t* - 1, Z_{it} represents other predetermined factors conceptually relevant to the likelihood of canker infection, and $\in_{it}$ 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 10-km^2 units, our measure of infection for the aggregate unit is the simple count of infections within the unit. Thus, we adopt two separate approaches to modelling 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:

$$d_{it} = f(X_{it}\beta), \tag{6}$$

using a probit model, where $d_{it} = 1$ if $y_{it} > 0$ and is zero otherwise. 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 10-km^2 unit directly. The Poisson count model is given by:

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

where λ represents the 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.

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.

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 denser 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 multiblock units in neighbouring units in the previous calendar year. Recall that neighbouring 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. Current 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.

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 probability 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 krigging procedures to estimate the probability surface. 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 neighbouring 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

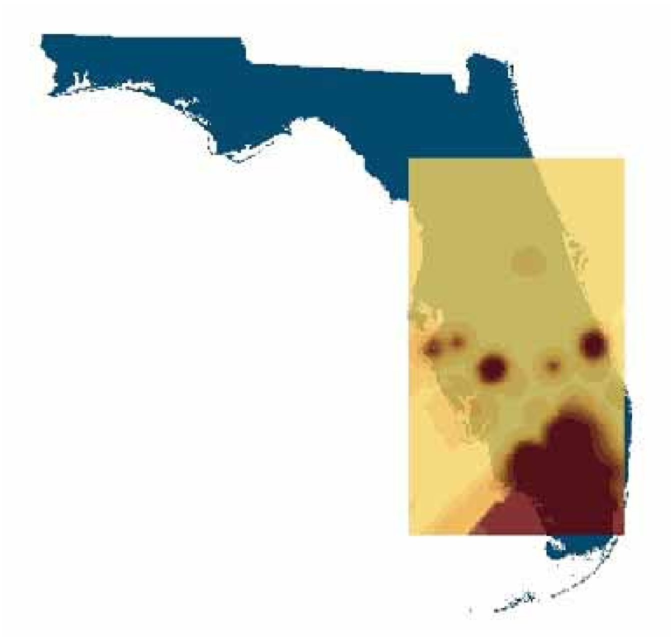

Figure 4*. Predicted probability surface using actual infection counts*

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 5.8 % of the aggregate observations have a positive infection status while only 2.5 % of the aggregate observations have positive finds. About 75 % 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 0.178 to 0.200, 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 suggest that oranges and tangerines have the lowest rates of infection, followed next by grapefruit and finally by other fruits (the default category), which consists of

***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)	0.0045	0.0667
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
…………..10-km^2 unit aggregates…………..			
Positive status	0/1 Indicator of a positive multiblock (up to 2 years after inspection)	0.0584	0.2346
Positive find	0/1 Indicator of positive canker survey	0.0252	0.1568
Orange share	Orange acreage share	0.7531	0.2922
Grapefruit share	Grapefruit acreage share	0.0917	0.1689
Tangerine share	Tangerine acreage share	0.0547	0.1292
Dormant share	Dormant acreage share	0.1098	0.2154
Positive neighbours (t-1)	Positive status units within 30km radius	1.9210	4.1317
Total acreage	Total unit acreage (hundred thousand acres)	0.0224	0.0412

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

lemons, limes and other minor citrus commodities. This finding is consistent with the implications of biological research, which has suggested that lemons, limes and grapefruits 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.

Table 4*. Probit model estimates of canker infection probabilities*[a]

Parameter	Estimate	Standard error	t-Ratio
..………………………Model of positive status……………………………………..			
Intercept	-0.7417	0.1364	-5.44*
Orange share	-1.4717	0.1524	-9.66*
Grapefruit share	-0.9383	0.2657	-3.53*
Tangerine share	-1.1121	0.3699	-3.01*
Dormant share	0.0280	0.1903	0.15
Positive neighbours (t-1)	0.0266	0.0095	2.80*
Total acreage	7.8289	0.7702	10.17*
Likelihood ratio test	180.77*		
McFadden's LRI	0.1706		
..………………………Model of positive finds……………………………………..			
Intercept	-1.0479	0.1647	-6.36*
Orange share	-1.5247	0.1938	-7.87*
Grapefruit share	-1.2725	0.3771	-3.37*
Tangerine share	-1.6060	0.7624	-2.11*
Dormant share	-0.3504	0.2632	-1.33
Positive neighbours (t-1)	0.0239	0.0126	1.90*
Total acreage	7.6514	0.9155	8.36*
Likelihood ratio test	111.95*		
McFadden's LRI	0.1999		

[a] Asterisks indicate statistical significance at the $\alpha = 0.10$ or smaller level.

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 neighbouring areas. The count of positive status multiblocks in all neighbouring units (defined by those units with centroids within 30 miles of the centre 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 neighbouring 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 neighbouring units.

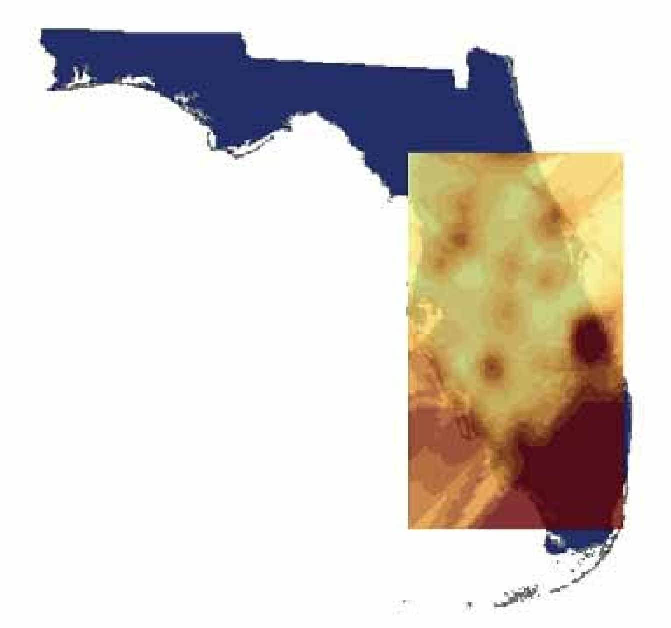

Figure 5*. Predicted probability surface using probit model*

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 modelling 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 5.

Table 5*. Poisson logarithmic count model estimates of canker infection counts*[a]

Parameter	Estimate	Standard error	t-Ratio
………………………Model of positive status……………………………………..			
Intercept	1.6697	0.05	33.39*
Orange share	-3.6185	0.0741	-48.83*
Grapefruit share	-2.4731	0.1519	-16.28*
Tangerine share	-2.6196	0.2683	-9.76*
Dormant share	-1.0238	0.0953	-10.74*
Positive neighbours (t-1)	0.0435	0.0049	8.88*
Total acreage	12.1193	0.2244	54.01*
Pearson's χ^2	31,598.98*		
………………………Model of positive finds……………………………………..			
Intercept	-0.3445	0.1377	-2.50*
Orange share	-3.6594	0.2065	-17.72*
Grapefruit share	-2.6479	0.4420	-5.99*
Tangerine share	-3.0237	0.8595	-3.52*
Dormant share	-1.3306	0.2893	-4.60*
Positive neighbours (t-1)	0.0530	0.0132	4.02*
Total acreage	12.0353	0.6389	18.84*
Pearson's χ^2	7,927.27*		

[a] Asterisks indicate statistical significance at the $\alpha = 0.10$ or smaller level.

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 being the least susceptible, followed by tangerines, grapefruits 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 neighbouring 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[10]. Figure 6 presents the estimated probability of infection obtained from the Poisson model of positive infection status. Again, a much richer probability surface is implied by recognition of the conditioning variables.

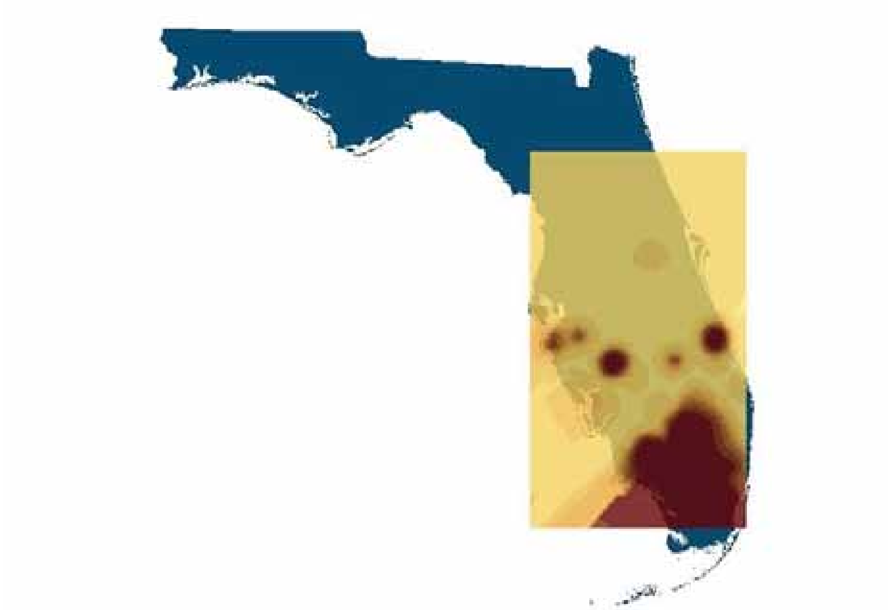

***Figure 6**. Predicted probability surface using Poisson model*

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 neighbouring areas also tend to be significantly related to infection risks.

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

$$E\{Loss_{iJ}\} = F_i(\cdot) \cdot G_J(\cdot) \cdot \text{Payment, for } i \in J, \quad (8)$$

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[11]. 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 0.0776.

Table 6 contains summary statistics for the estimated premiums for individual multiblocks. The premiums differ substantially across the alternative models, ranging from an average of $19.18 per acre for the probit model of positive finds to $229.63 for the Poisson model of positive canker status. The Poisson models may be suspect in light of the relatively rare nature of canker infections (less than 5 %). This may lead to a 'zero-inflation' problem that makes standard Poisson regression models suspect[12]. In all models, the highest premiums are in excess of $700 per acre each year – suggesting an infection probability of about 7 %. The dispersion of premiums is illustrated by Figures 5 and 6, which present the probabilities of infection determined from the aggregate-unit models. Note that the premiums are given by the product of the estimated infection probability at the aggregate-unit level, the multiblock conditional probability of infection (0.0776) and the payment ($10,000). The figures demonstrate that the premiums are highest in those areas that have realized the greatest incidence of canker infections. This includes those areas in the southern part of the state in the vicinity of Miami.

***Table 6**. Summary statistics on premiums ($/acre) for canker coverage*

Model	Mean	Standard Deviation	Min	Max
Probit on Positives	44.53	62.67	10.43	746.22
Probit on Positive Finds	19.18	38.68	1.06	703.27
Poisson on Positives	229.63	176.68	38.75	776.00
Poisson on Positive Finds	48.26	83.40	3.74	775.80

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 checkoff 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 risk 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 neighbouring 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. 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. A wider array of empirical models that may be more flexible and more appropriate to the canker infection problem are currently being investigated. A specific interest is the suspected 'zero-inflation' problems associated with the relatively rare occurrence of canker in our data. In addition, several hurricane events that occurred 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 was undertaken in mid-2005. As additional data are made available, we will focus modelling 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.

NOTES

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[1] The current citrus canker infestation was detected in Florida on September 28, 1995. However, officials have identified five commercial citrus groves in Manatee and Highlands counties that were destroyed in previous limited outbreaks that occurred between 1986 and 1990 (USDA-APHIS 2002).

[2] RBUP indicates protection purchased at higher levels of coverage (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).

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

[4] 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.

[5] See Goodwin and Smith (1995) for a detailed discussion of contract design issues associated with all-risk crop insurance plans.
[6] 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.
[7] 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.
[8] The geographic centroid is the 'centre 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 canters of the 10-km^2 units.
[9] This raises an interesting point about our modelling exercise. We are not actually modelling 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.
[10] 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.
[11] 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 are 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.
[12] Current research is focusing on more general count data regression models, including models that explicitly address the overinflation problem.

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