An Agent Based Model of ACP/HLB in California Citrus - Preliminary Results on the Effects of Insecticide and Coordination on the Spread of HLB

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Funding provided by USDA-NIFA Emergency Citrus Disease Research and Extension Grants

Research Note 2021-2
December 2021

California State University Sacramento

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Issue

In the late 18th century, a citrus disease called die-back began to take hold in India (Gottwald, da Graça, and Bassanezi 2007). Around the same time, a similar phenomenon was noticed by farmers in Southern China and referred to as huanglongbing (HLB) (da Graça and Korsten 2004). The bacterium *Candidatus Liberibacter asiaticus*, the presumptive causal agent for HLB, infects a tree's phloem, suffocating the roots causing the tree to die. Once HLB infects a tree, it quickly spreads throughout the tree (Farnsworth et al. 2014). Even if a tree survives initial infection, much of its fruit does not fully ripen, leading some to refer to HLB as citrus greening disease. The fruit also becomes inedible and the cost for treating an endemic grove is high as removal of infected trees and those near it are likely required. Since its discovery in Asia, HLB has spread to more than 40 countries across Asia, Africa, and the Americas (Bové 2006).

In 1998, the Asian Citrus Psyllid (ACP), the primary vector for HLB, was discovered in Florida and within seven years HLB was detected in Dade County in southern Florida, causing an estimated $4.5 billion impact on the Florida economy between 2007 and 2011 (Alvarez et al. 2016, Farnsworth et al. 2014; Hodges and Spreen 2012) and decreased production by an estimated 8 million tons per year between 2004 and 2020 (Simnett and Kramer 2020). In 2008, ACP was detected in San Diego County, California and is now established throughout southern California in both residential and commercial citrus trees (Byrne et al. 2018; Hoddle 2012). Because of the risk of HLB, California's citrus industry must have an effective response to avoid repeating the disaster experienced in Florida. That response will entail a better understanding of the rate of transmission and spread of the disease, effective management practices, the rate of farmer adoption of those practices, and needed rate of cooperation to adequately address HLB. With no known control for HLB to date, the only effective management of disease spread is vector control; necessitating the need for monitoring, reporting, and area-wide cooperation between growers. Estimating the rate of spread entails assessing the biology, geography, and population dynamics of ACP (Gottwald, Luo, and McRoberts 2014). However, vector control to mitigate the risk and severity of infection will require a coupling between the bio-physical conditions of disease spread with possible grower response rates. Considering the bio-physical and human dimensions of disease spread will help us better understand, and communicate, when and where possible outbreaks of the disease may occur and more accurately assess a grower's risk of infection.

Study Method

To gain insight into this problem, we constructed an Agent Based Model (ABM) of 9 citrus growers, their citrus trees, and invading ACP which can infect the trees with HLB. The model consists of a 33x75 lattice, with each cell representing a citrus flush patch. Nine groves of size 11x25 are assigned to growers who are identified by their position in the 3x3 grower grid. We then simulate the spread of ACP/HLB by introducing infected ACP into varying positions on the grid on day 80 of the 5-year simulation. Our model uses the same parameters as Lee (2015), extending their model to the 9-grove case. In California's Psyllid Management Areas (PMA), growers are encouraged to apply insecticide effective against ACP on specified dates throughout the year.[1] In our analysis we consider how different degrees of compliance with these spraying dates influence how HLB spreads. There are 3 intervention strategies available to growers. We define Group/Coordinated Action as spraying within a 21-day window of the designated dates, and Individual Action as spraying within a 60-day window of the dates. The day a grower chooses to spray is randomly determined in the window provided by the intervention strategy they choose. Growers can also choose to no intervention, which we call No Action. We then examine how different combinations of window size, PMA cooperation, and insecticide efficacy influence how long it takes HLB to reach a grove (defined in this study as survival time).

Key Insights

When evaluating optimal strategies under complete coordination, efficacy of insecticide is the primary factor in increasing survival times. Decreasing the spraying window (i.e., greater spray coordination) has negligible effects unless efficacy is 85%. At this level there is a clear difference amongst the window sizes tested, with the 21-day window having on average 20.67% higher survival times then the 60-day window. In simulations with variable coordination, the level of coordination (defined as implementing the Group Action strategy) amongst a grower's neighbors is the main driver in increased survival times. When no neighbors are coordinating, a grower's own choice of strategy has no effect on survival times. Only at 85% efficacy and complete coordination does a grower's strategy have a significant effect on survival time, with Individual and Group Action having on average 20.1% longer survival times than No Action. However, there is no significant difference in survival times between Individual and Group Action in this case.

Detailed Findings

We first examine how survival times change under complete coordination. All growers comply with the intervention parameters provided, and we test each set of parameters across 54 different combinations of invasion location and distribution. Figure 1 shows stratified Kaplan-Meier curves for these data.[2] Efficacy causes

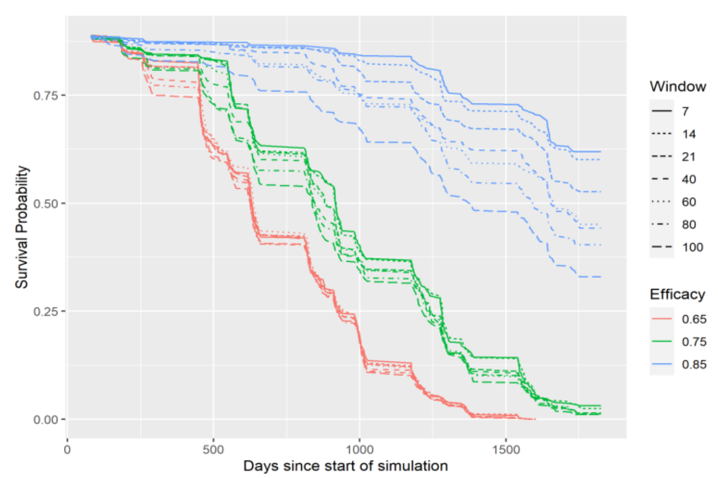

Figure 1. Kaplan-Meier survival curve under complete coordination and for varying window lengths and efficacies

[1] See https://ucanr.edu/sites/ACP/Grower Options/Grower Management/Eradication Strategies/ and https://citrusinsider.org/psyllid-and-disease-control/treatments/treatment-schedules-by-region/ for more information.

[2] See Goel, Khanna, and Kishore (2010) for details on Kaplan Meier curves

the largest change in survival probability, with changes in window size having a significant effect only when efficacy is 85%.

To formalize these findings, we fit an Accelerated Failure Time (AFT) model to the data, following guidance in Wei (1992). We test a linear specification and another that allows for interaction between efficacy and window size. After testing both specifications across 6 distributions, and based on the Akaike Information Criterion (AIC), the specification with an underlying Weibull distribution is selected for conducting inference.

The AFT model results align with our previous observations. Indicator variables for 75% and 85% efficacy are significant, and the magnitude for the coefficient on 85% efficacy is over 4 times that of the 75% efficacy coefficient. This corresponds to a 36% increase in survival time at the 75% efficacy level, and a 289% increase in survival time at the 85% efficacy level (all else held constant). Window size is not significant at the 65% level, nor is it significant when combined with 75% efficacy. At the 85% level, however, a 1-day increase in spraying window corresponds to a 0.53% decrease in survival time. That is, a 10-day increase in window size corresponds to a 5.3% decrease in survival time. Next, we test data from simulations using the three intervention strategies defined above. These data were generated by running simulations where each of the 9 growers uses each of 3 strategies while their neighbors either use the No Action strategy (Neighbor Coordination of 0) or the Group Action strategy (Neighbor Coordination of 1). These simulations are then run for each of the 54 possible invasion scenarios. Figures 2, 3, and 4 show Kaplan-Meier curves for 65%, 75%, and 85% efficacy, respectively. At all efficacy levels, coordination is the main influence increasing survival times. At the 85% level, we also see an increase in survival times for spraying strategies with complete neighbor coordination. We once again fit an AFT model to the data to formalize the results. Three specifications were

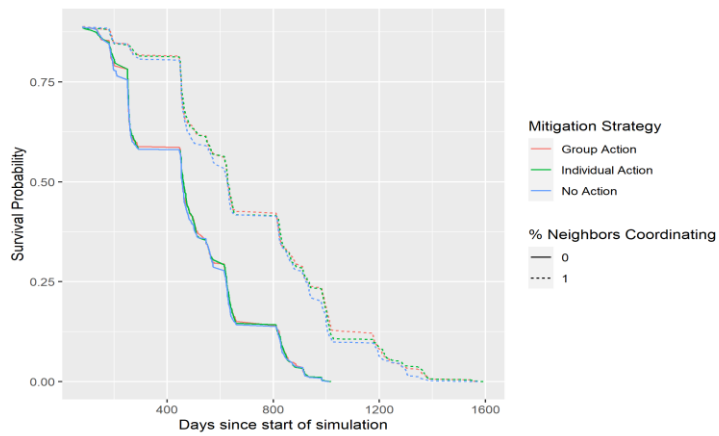

Figure 2. Kaplan-Meier curves by strategy and coordination, 65% efficacy

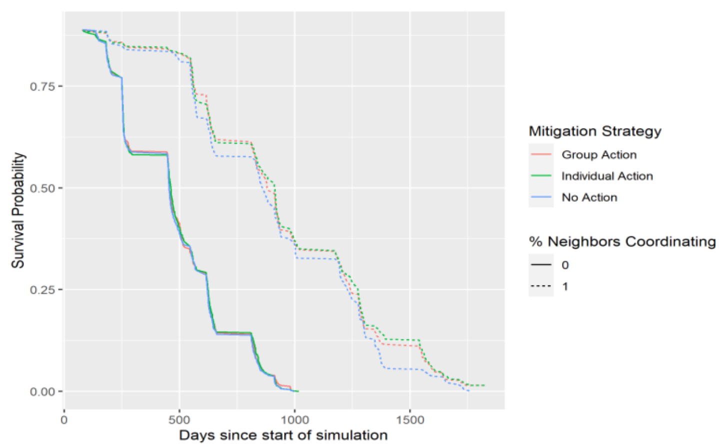

Figure 3. Kaplan-Meier curves by strategy and coordination, 75% efficacy

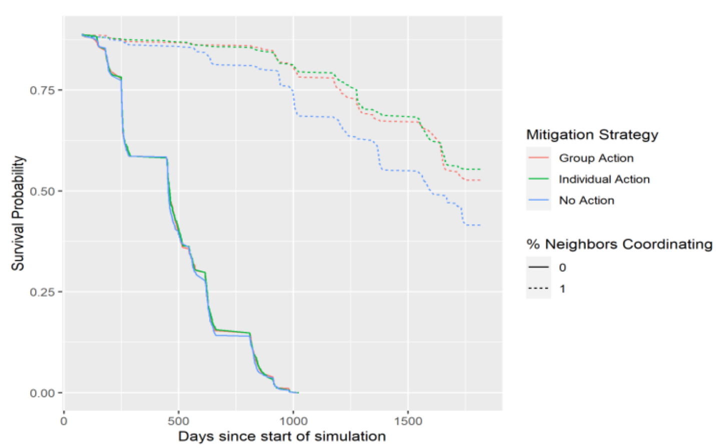

Figure 4. Kaplan-Meier curves by strategy and coordination, 85% efficacy

tested across 6 distributions, and we used AIC to choose the model for inference. The specification chosen has interaction terms between coordination level and efficacy, as well as an indicator variable term to capture the effect of spraying strategies at 85%.

The coefficients on coordination and all the interaction terms are highly statistically significant, but strategy and efficacy terms in isolation (their effect on the base case of 65% efficacy and no coordination) are not. Complete coordination increases survival time by 48.6%, 32.2%, and 172.8% for 65%, 75%, and 85% efficacies, respectively. Employing a spraying strategy when efficacy is 85% with full coordination increases survival time by 20.1%.

For more information about this study contact: Ajay Singh (singh@csus.edu) or Jonathan Kaplan (kaplanj@csus.edu)

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