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Are avocados toast? A framework to analyze decision-making for emerging epidemics, applied to laurel wilt

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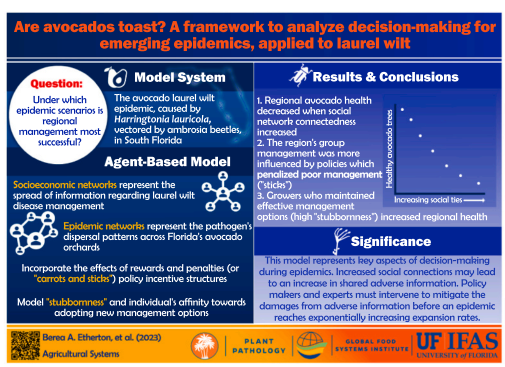
HIGHLIGHTS

- We introduce a new agent-based model for scenario analysis of regional disease management, applied to avocado laurel wilt.
- An increase in social connections negatively impacted opinions regarding efficient management and thus regional health.
- Regional health increased under policies which penalized individuals for practicing less efficient management strategies.
- Individuals who refused to adopt less expensive and less effective management strategies benefited regional health.
- Collective action during emerging epidemics will operate best when specialists inform policy makers and decision makers.

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: When emerging pathogens threaten global food security, collective action for disease management is key for protecting food systems. We evaluate how the informal exchange of information about epidemic and economic outcomes can influence the management decisions of individuals and the resulting epidemics, in the context of the avocado laurel wilt epidemic in south Florida.
OBJECTIVES: In scenario analyses, we addressed how socioeconomic networks, laurel wilt epidemic networks, policy incentive structures, and social behaviors combine to influence (a) information exchange across this region, (b) growers' decisions about disease management, and (c) epidemic spread and yield loss. We identified the scenarios in which regional avocado health fared best.
METHODS: We built an agent-based model to simulate laurel wilt epidemic expansion and establishment across south Florida over a 10-year period. The model used parameters specific to patterns observed and quantified from the laurel wilt epidemic in south Florida. Based on the locations and sizes of avocado orchards there, we simulated disease expansion and information dissemination through multilayer socioeconomic and epidemic networks and evaluated the effects of "carrot" and "stick" policy incentive structures and behaviors like "stubbornness" in decision making. Scenarios were simulated for multiple parameters across a 10-year time period, and the regional health of avocado and management decisions of growers were analyzed.
RESULTS AND CONCLUSIONS: Increased social connections led to lower regional crop health due to increased exchange of information reinforcing selection of less expensive but less effective management choices. This information exchange was particularly impactful during the lag phase of epidemic expansion, when the cost of disease management outweighed the cost of disease. Managers who were resistant or "stubborn" against adopting these less expensive and less effective management strategies, particularly during the lag phase of epidemic expansion, contributed to greater regional health. In these scenarios, growers responded more to policies which penalized individuals than to policies which rewarded individuals.
SIGNIFICANCE: By quantifying varying degrees of stubbornness, and how growers may weight past experiences and new information, we represented key aspects of decision making and its many influences on regional collective action in this novel agent-based model. The model demonstrates the caveats of information exchange across social networks during epidemics, and the valuable role that policy makers and informed educators can have, particularly during the lag phase of epidemic expansion. Decision makers and stakeholders must understand the influences of information exchange to overcome the challenges of collective action for crop health.

1. Introduction

Invasive pathogens and pests are a primary concern for protecting food security and maintaining agricultural productivity. In this study, we address the challenge of regional crop health management in the onset of an emerging epidemic, when the decisions of many individuals can dictate epidemic outcomes, for example, during quarantines or the distribution of preventative treatments. A region generally fares best when the community cooperates collectively to manage disease, though collective action and the successful implementation of new technology are often dependent on a multitude of factors, including socio-technical perceptions, human-environment and socioeconomic networks, the role of institutions, and the perceived epidemic threat (Clark and Harley, 2020; Garcia-Figuera et al., 2021; Ostrom, 2010).

Collective action is heavily dependent on a community's size, where larger groups are often less likely to be successful (Hardin, 2015; Olson, 1989; Ostrom, 2010). It might be expected that in larger communities, individuals will fare better given more access to resources, like informed evidence, infrastructure, or financial support, though larger communities must allocate limited resources and are more likely to include individuals who deviate from effective and accepted management strategies, potentially influencing their associates' management outcomes. Within and between agricultural communities, socioeconomic networks form, where individuals communicate casual information regarding their perception about an epidemic's threat and the costs and benefits of available management options. Growers' decisions about how to manage emerging epidemics may be based on casual information exchange regarding disease management options in these socioeconomic networks, and their own past experiences. (Carroll et al., 2017; Hillis et al., 2017; Kiros-Meles and Abang, 2008). Growers also may be influenced by agencies or extension specialists through informed agitation, or the purposeful interjection of more technical information into a socioeconomic network (Clark and Harley, 2020). Some individuals, though, may be "stubborn" about their opinions, being less likely to move from their current state (Botte et al., 2022; Ghaderi and Srikant, 2014) even as more information becomes available. An individual's level of "stubbornness" is used in our study to represent the many facets which influence an individual's likelihood of changing their mind, including both socioeconomic influences, and personal biases, generally. Depending on the context, stubbornness in this sense can be good or bad for a system. In epidemic management, as the number of individuals who reject the recommended or most effective management increases, the type of information spread within a socioeconomic network can become detrimental towards collective action for regional health. Successful collective action for disease management can be seen as reaching "herd immunity," where a sufficient proportion of the community is protected against disease to protect the entire community.

During the onset of an epidemic, the decisions growers make to protect themselves against disease might not be as effective as during the subsequent stages of an epidemic. Epidemics may exhibit linear, biphasic or exponential expansion over time, where the expansion type is dependent on the group's size and distribution (Bar-David et al., 2006; Shigesada and Kawasaki, 1997). Each epidemic will have a unique set of phases; for example, epidemics can experience a lag phase, or slower or delayed rates of expansion, an acceleration phase, or rapid expansion, and an extinction phase, where susceptible hosts (and thus, disease rates) drastically diminish (Grenfell and Harwood, 1997; Hui and Richardson, 2017). As more data is obtained regarding mortality rates, dispersal mechanisms, or broadly, the population dynamics, growers must adapt their management techniques to best protect themselves and their region from disease in subsequent epidemic phases (Hui and Richardson, 2017).

Where the success of collective action and implementation of new management technologies is uncertain, models can be used to study the effects of regional management implementation across time and unique epidemic phases (Funk et al., 2010; Garcia Figuera et al., 2022; Garrett, 2021; Shaw and Pautasso, 2014; Murray-Watson et al., 2022). Epidemic models can be designed to address the unique characteristics of coupled human-environment networks to understand and predict pathogen or insect spread and to reproduce aspects of inter- and intraregional disease expansion (Garrett et al., 2018; Moslonka-Lefebvre et al., 2011; Mundt et al., 2011; Pautasso and Jeger, 2008; Plantegenest et al., 2007). In this study, we evaluate the ways in which regional collective action towards disease management may be encouraged in multilayer human-environment and socioeconomic networks, using an agent-based model (Grimm et al., 2006) to address the onset of the laurel wilt disease epidemic in avocado (*Persea americana*) in southern Florida. Avocado, native to Mexico and Central America, is a high value crop with a high fat, starch, and caloric profile, and is a highly nutritional food (Araújo et al., 2018). Laurel wilt, caused by the fungus *Harringtonia lauricola* (formerly *Raffaelea lauricola*), was first reported in the United States near Port Wentworth, Georgia, in 2002, and threatens the avocado industry, which has exports projected to reach \$8.3 billion globally by 2030 (OECD/FAO, 2021; Olatinwo et al., 2021; Kendra et al., 2013). Laurel wilt, like COVID-19 and citrus huanglongbing, is an example of an epidemic with rapid expansion, demanding community cooperation for effective management, and with devastating effects on hosts (Singerman and Rogers, 2020).

H. lauricola can infect many tree species in the Lauraceae, and since its introduction in 2002, roughly 300 million redbay (*Persea borbonia*) trees been killed by laurel wilt, approximately a third of the native population (Choudhury et al., 2021; Hanula et al., 2008; Ploetz et al., 2017b). *H. lauricola* is vectored by several ambrosia beetle species, particularly *Xyleborus glabratus* in avocado. Ambrosia beetles locate host trees based on visual and olfactory signals, burrow into the limb and trunk wood and introduce the fungus, causing epidemic expansion (Carrillo et al., 2014; Kendra et al., 2013; Ploetz et al., 2017a). Trees respond to disease through a hypersensitive response, leading to the death of a tree often within three or four weeks, which may result in a 50–75% (\$15–22.5 million) reduction in profit through lost sales, property damage, and increased management costs in Florida alone (Evans and Ballen, 2015; Evans et al., 2010; Ploetz et al., 2017b). Laurel wilt disease has currently not been reported in California or Mexico, where it has the potential to devastate the industry. There is also currently no economically practical and effective management effort, so growers rely on a variety of management options, making collective action difficult (Crane et al., 2020a; Crane et al., 2016; Crane et al., 2020b; Mosquera et al., 2015). Growers that choose to practice the most effective yet most expensive management effort will benefit the region through protecting their grove against disease, though they risk their economic viability; conversely, growers who choose not to manage their grove may secure short-term economic viability but risk the health of their grove and the surrounding region.

Policy-based incentive structures have commonly been used to influence individual decision making, by encouraging individuals to adopt sustainable management practices despite management accessibility or cost (Clark and Harley, 2020; Costa, 2021). One formal strategy for managing group behavior is to create policies that incentivize behaviors which benefit the group and penalize behavior that may be detrimental to the group (Oliver, 1980). Such policy incentive strategies have been successfully implemented for influencing group cooperation (Andreoni et al., 2003; Oliver, 1980; Zimmermann et al., 2018). One policy strategy, often referred to as a “carrot,” rewards actions that provide a regional benefit, and can include compensation for the costs of management options or infrastructure, or free educational courses or technical advice (Barrett et al., 2016). For example, avocado growers in south Florida were provided cost-share funds to remove dead avocado trees which are a source of infection risk for other orchards, and replant avocado trees (personal observation, J. Crane). Another policy option, referred to as a “stick,” is a penalty for behavior which may worsen a region’s health or economic standing, including increased tax rates, additional fees, or exclusion from group activities (Costa, 2021). For example, in south Florida, growers (or land speculators) who do not remove laurel wilt infected or dead trees may lose their agricultural land tax exemption if they allow dead trees to remain on their property, resulting in their property being taxed at the urban-land rate (personal observation, J. Crane). These policies are valuable for regional collective action and management intervention, as they tend to address the inequity of accessibility to sustainable, yet more expensive, management options, and address those individuals who may be purposefully negligent towards management for personal financial gain.

Agent-based models and multilayer networks provide a framework for describing spatiotemporal socioeconomic and epidemic interactions (Garrett, 2021; Gent et al., 2019; Grimm et al., 2006; Manfredi and D’Onofrio, 2013; Pacilly et al., 2016; Xing et al., 2020). In this study, we simulate epidemic risk across the south Florida avocado landscape, with the relative likelihood of spread between two locations described by a gravity model. Gravity models are commonly used in agent-based and epidemic modeling to evaluate the movement of pests and pathogens (Andersen, 2019; Andersen Onofre et al., 2021; Jongejans et al., 2015; Rauch, 2016; Xing et al., 2020). In our gravity model, orchards with higher host (avocado tree) density and closer proximity to other orchards are at higher risk for pathogen spread and establishment. The south Florida avocado production area is relatively small, where over 90% of avocado production takes place within 14 mile^2, and orchards tend to be clustered near each other (Fig. 2). We also simulate information exchange among south Florida avocado growers, with the relative likelihood of exchange between two growers represented by an inverse power law function of distance, weighted to incorporate homophily, or assortativity, based on growers’ management preferences. The inverse power law, generating a scale-free network, is widely used to model the flow of people, goods, and social interactions, which are more likely to occur with spatial proximity (Barabási, 2009; Barabási and Albert, 1999; Catanzaro et al., 2004; Taylor and Openshaw, 1975). Homophily, or the tendency for an individual to preferentially associate with those who are similar, is a common feature of networks (Catanzaro et al., 2004; Fu et al., 2012; McPherson et al., 2001; Papadopoulos et al., 2012). Both the epidemic and information exchange networks are dependent and directly influenced by spatial proximity, where the probability of both dispersal and association decays with distance.

The challenges for effective disease management in communities of decision makers are seen across pathosystems, from COVID-19 to citrus huanglongbing, and across invasion biology more generally. Understanding the diffusion dynamics and clustering of information and disease across multilayer networks is a key perspective for epidemic management, as illustrated for example in Zhuang and Yağan (2016). We incorporate these effects and add quantification of an individual’s perception of new information obtained through casual social interactions, studying how collective management responds to informal communication across epidemic phases. We assess scenarios for multilayer socioeconomic and epidemic networks based on avocado production in the south Florida avocado industry, with approximately 1 K orchards totaling 8.5 K acres of avocado production. We integrate the effects of social behavior, like level of stubbornness, and policy incentive structures; we identify what types of influences and potential scenarios are more successful in influencing collective action towards successful regional disease management during the onset of simulated laurel wilt epidemics, and across ten-year expansion periods (Fig. 1). We build an agent-based model to address three main questions. (i) How can varying dispersal kernels for pathogen spread and for patterns of socioeconomic network connectivity affect avocado health across individual and regional orchards? (ii) Which policy-based incentive structures – carrot, stick, or combination – best influence the collective action towards more sustainable management adoption? (iii) How can a grower’s level of stubbornness affect individual orchard health and regional health throughout an epidemic? These scenarios illustrate the general challenges for agricultural decision makers and other stakeholders when information exchange occurs informally. They also provide perspective for planning in anticipation of new epidemics, as diseases such as laurel wilt are found in new states and countries.

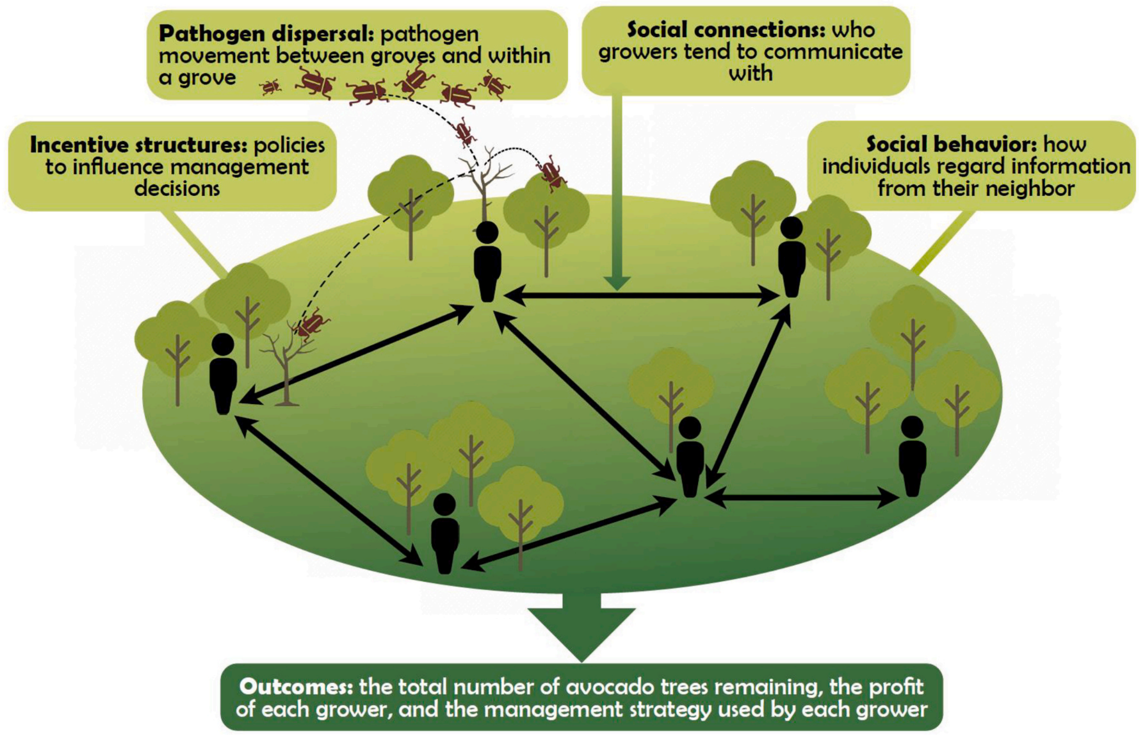

Fig. 1. The agent-based model used in this study incorporates multiple influences on an epidemic. As a pathogen disperses across a region, growers communicate through their social connections about how best to protect their orchard against disease. These social and epidemic networks, along with social behaviors and incentive structures, all can influence individual decision-making and the outcome of an epidemic.

2. Materials and methods

2.1. Agent-based model design

The agent-based model (ABM) (Grimm et al., 2006) used in these scenario analyses is presented here in terms of the purpose, design concepts, initialization, and sub-models, with more details in **SM 1.** Parameters and dispersal models were chosen based on experimental results and observations of the ongoing laurel wilt epidemic in south Florida.

2.1.1. Purpose

The purpose of this ABM is to evaluate how the collective choices of growers influence regional outcomes for an invasive pathogen or pest. The model is applied to avocado growers in south Florida who respond to the laurel wilt epidemic across a range of scenarios. This framework simulates the onset of epidemics across a time series and is designed to support the decisions of policy makers who are considering how policy incentive structures can best improve regional management adoption, optimize resource allocation, and mitigate disease expansion and establishment. We used sensitivity analyses (or uncertainty quantification) to capture variability across multiple parameter values, to represent a range of scenarios for levels of an individual's stubbornness, disease dispersal rate, average socioeconomic network node degree, and for varying degrees of carrot and stick policies.

2.1.2. Design concepts

This model adds several new design concepts to the multilayer network model in Garrett (2021). In this new model, growers may choose from three levels of management intensity, referred to as low, medium, or high management, which protects their orchard from disease establishment and expansion to varying degrees. A low management level does not protect against disease expansion/establishment, whereas high management, will provide high protection. Growers determine which management level (low, medium, or high) they will adopt each year based on their perception of the profit they may gain from using that management level. Growers interact with other growers with whom they are linked in a socioeconomic network and share information about their chosen management levels and the annual profit gained from using their chosen management level. There are no external sources of information and growers only make their decisions about management based on the interactions in their socioeconomic network. Through evaluating other growers' orchard health and economic standing when applying each of the management levels, growers then predict which level may best benefit their orchard in the following year.

A grower's financial fitness is determined by their ability to maintain avocado trees and economic profit across a 10-year period. Growers accumulate profit earned from their fruit-bearing avocado trees and spend their profit on a disease management level, where the low management level has the lowest costs, and the high management level has the highest costs. Growers that run out of financial resources or fruit-bearing avocado trees leave the avocado industry, and other growers retain the perception that the management level chosen by those who left was unsuccessful. Growers do not replant lost trees in these scenarios given these new trees take roughly 6–8 years to become economically viable, so we excluded replanting from our models.

This ABM is stochastic. The disease dispersal network is redrawn every timestep (where one timestep is one month) to reflect variation in ambrosia beetle movement, dependent on weather, temperature, relative humidity, and tree size and diameter (Choudhury et al., 2021). The socioeconomic network is redrawn between realizations and remains constant throughout a single realization, or across 10 years (120-time steps). The rate of disease expansion and establishment is stochastic, with mean rates based on the grower's management level; for example, some growers who adopt the highest management level may still experience disease establishment or expansion, although it is less likely.

2.1.3. Initialization

For simplicity, scenarios include one orchard manager (one decision maker) per avocado orchard. The growers' geographic locations and orchard acreage are based on a map of the avocado orchards in the Homestead region obtained from the Florida Water Management District. These geographic locations and relative acreage are constant across simulations and are used to build the socioeconomic and epidemic networks, discussed later in more depth. The starting available profit for each grower is proportional to the orchard's size, where there are approximately 100 avocado trees per acre (De Oleo et al., 2014; Kuack, 2019). Growers are randomly assigned an initial disease status (infected or not infected), a preferred management level, and a perception of the economic returns from the other management levels. Growers are given a level of stubbornness, which is constant across growers for each realization (discussed later in 2.2.3 Perceived benefit of adoption). A policy stick value (applied as a property tax % increase) and policy carrot value (applied as available funds to cover management costs) are assigned at the beginning of each realization, where the percent tax increase value remains constant across the time series in a realization, and the management funds diminish as growers use them over time.

2.1.4. Process overview and scheduling

Initializing a realization, we generate a socioeconomic network of growers, each with a chosen management strategy, beliefs about other management strategies, a level of stubbornness, an avocado orchard location and the orchard's respective acreage based on the maps of Homestead's avocado orchards, a starting available capital, healthy avocado trees (100 trees/acre), and a disease status. The model moves in one month time steps, and simulations were performed over 120-times steps, or 10 years. Once laurel wilt has become established within an orchard, it expands within the orchard at a rate based on the orchard's current management level, and infected trees die one month after becoming infected (Crane et al., 2020b). A realization proceeds as follows:

1. A round of disease expansion and establishment occurs simultaneously, where the probability of laurel wilt expansion and establishment is a function of each orchard's management level.
2. Growers communicate with the other growers within their socioeconomic network about their success with their current management strategy.
3. Growers update their current beliefs about the three management levels based on the information they received from their contemporaries, and their own past beliefs and experiences.
4. Steps 1–3 are repeated for 11-time steps.
5. Every 12th time step (at the start of a new year), growers may change which management level they choose to implement the following year. Growers use the information they have collected about the success of other growers in their socioeconomic network over the past year and their own success, to determine which management level they will now adopt. Growers receive an annual profit based on the number of healthy fruit-producing trees remaining in their orchard and their management expenses.

2.2. Submodels

2.2.1. Socioeconomic network construction

An adjacency matrix is generated where each row and column represent one of the 1132 avocado orchards around Homestead, Florida. The socioeconomic network structure is simulated to understand the effects of potential social structures. First, suppose that growers are more likely to communicate with other growers in close geographic proximity to them, such that communication rates decay with distance. Each entry in the adjacency matrix is evaluated using an inverse power law model (Barabási, 2009; Barabási and Albert, 1999), $y = L_{jk}^{-\beta_{social}}$, where L_{jk} is the distance between two nodes j and k ($j \in [1,1132], k \in [1,1132], j \neq k$), β_{social} is the connectivity parameter, and y is the probability that the two nodes j and k will be linked. Next, suppose that growers have a higher probability of associating with other growers who share the same choice of management at the beginning of a realization (McPherson et al., 2001; Papadopoulos et al., 2012). Growers who share the same management level are given a link weight of 0.4, whereas two growers who do not practice the same management strategy are given a weight of 0.1. We estimated these parameters based on observations from extension specialists who have been working with avocado growers in Florida for over 10 years and are familiar with social dynamics across the region. Growers were observed to associate closely with other nearby growers, and to associate with other growers with a mild preference (homophily) towards other growers with similar management strategies or who use the same management company. If two growers were not nearby, and did not have similar management strategies, there is roughly a 10% chance they would communicate, for example, at Avocado Administrative Committee meetings, even if they tend to disagree about management strategies. Observed communication in south Florida is heavily weighted towards spatial proximity, with a mild bias towards homophily based on management choices, and these weights were chosen to reflect these social tendencies. The inverse power law adjacency matrix is multiplied elementwise by the shared-management link weights to produce a matrix representing the probability of two growers communicating. The elements of this matrix are then scaled between 0 and 1, and the rescaled probabilities of communication are used to generate the socioeconomic network used across one realization (Fig. 2**, B**). Here we use spatial distributions of avocado orchards and homophily (similarity in management choices) to model the types of communication networks observed in south Florida.

2.2.2. Epidemic network construction

An adjacency matrix for the epidemic network is generated where, again, each row and column represents one of the 1132 avocado orchards. Each entry in this adjacency matrix follows a gravity model, $y = D_j D_k L_{jk}^{-\beta_{epidemic}}$, where D_j and D_k represent the orchard size (in acres) for the orchards j and k, $\beta_{epidemic}$ represents the pathogen dispersal parameter, and y is the probability that pathogen dispersal occurs between orchards j and k. This adjacency matrix is then rescaled between 0 and 1. At each time step, pathogen dispersal between two orchards is stochastic and dispersal occurs, or not, as a function of the probabilities in the epidemic adjacency matrix (Fig. 2**, A**). Here we use both orchard acreage and spatial distribution to characterize and model the epidemic networks that are likely to occur in Homestead.

2.2.3. Perceived benefit of adoption

Growers perceive the success of the management levels (low, medium, or high) based on their observations of the associates they are linked to in the socioeconomic network and their own success. Growers communicate with their associates about: 1) their management level being used, and 2) their yearly profit. For model simplicity, growers can observe the yearly profit of their associates without error. Growers then average the observations about profit for associates within their socioeconomic network separately for each management level practiced. The management level with the highest average yearly profit across years is seen as the most successful management option and adopted by a grower in the following year.

The perceived benefits are weighted to reflect a grower's tendency to adopt new management levels through gauging the value of a new management based on a grower's own past experiences and new information, weighted to reflect an individual's "stubbornness" (Behrens et al., 2007; Botte et al., 2022). Here, the higher an individual's stubbornness, the lower the weight given to new information; conversely, individuals having a lower stubbornness will give a higher weight to new information (Ghaderi and Srikant, 2013; Yin et al., 2019). The following is the cumulative weighted financial benefit each grower

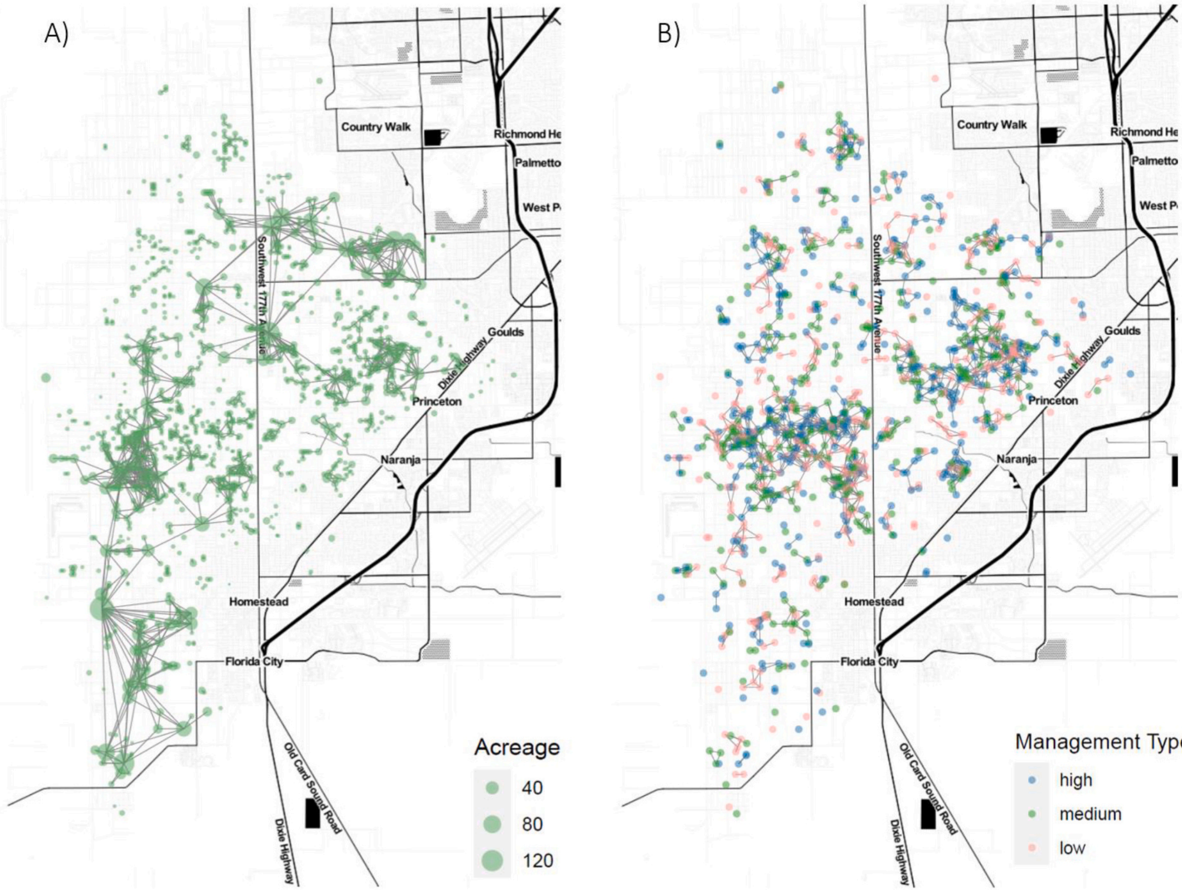

Fig. 2. An example of a multilayer network scenario in Homestead, Florida, where A) is an epidemic network of orchards, based on the gravity model with $\beta = 2.0$ and B) is a social network, based on the inverse-power model with $\beta = 1.5$. Network node locations are jittered for anonymity.

observes through the influences of socially linked associates. The cumulative weighted financial benefit $C_{ij(t)}$ for management level i of grower j at time t is

$$C_{ij(t)} = s_j C_{ij(t-1)} + (1 - s_j)\left[\frac{P^*_{ij(t-1)} + B_{ij(t-1)}}{N_{ij(t-1)} + 1}\right] \quad (1)$$

where i is the management level (i=low, medium, or high), j is the grower of interest ($j \in [1, 1132]$, t is the time step (measured in months, $1 \le t \le 120$), and s_j is the level of stubbornness of grower j ($0.1 \le s_j \le 0.9$). Here we chose to exclude $s_j = \{0, 1\}$, as these terms represent a "perfectly stubborn" individual ($s_j = 1$), and a "perfectly credulous" individual ($s_j = 0$). The term $s_j C_{ij(t-1)}$ represents the degree of tendency to weight one's previous perceptions about management levels more than new observations. The second term $(1 - s_j)\left[\frac{P^*_{ij(t)} + B_{ij(t-1)}}{N_{ij(t)} + 1}\right]$ represents the degree of tendency to weight newer observations about management levels in addition to previous observations.

The value s_j stays constant across one realization for a grower j. If $s_j < 0.5$, a grower would be more likely to consider adopting management levels given their new observations or information, if $s_j > 0.5$, a grower would be more likely to prefer their own management level and disregard new observations and information.

$P^*_{ij(t-1)}$ is the profit earned by grower j at the time $t - 1$ for using management i, where if the grower does not use the management i at time $t - 1$, $P^*_{ij(t-1)} = 0$. $B_{ij(t-1)}$ is the profit earned by grower j's associates, for associates who used management i at time $t - 1$. $N_{ij(t-1)}$ is the total number of associates of grower j that practice management i at time $t - 1$. $B_{ij(t-1)}$ is the profit earned by grower j's associates, for associates who used management i at time $t - 1$. $B_{ij(t)}$ and $N_{ij(t-1)}$ are defined by the following:

First, let there be an indicator function $L_{jk(t)}$, where $L_{jk(t)} = 1$ if growers j and k ($j \ne k$) are linked in the socioeconomic network at time t, where $k \in [1, 1132]$ and $L_{jk(t)} = 0$ otherwise.

Let there be an indicator function $I_{ik(t)}$, where $I_{ik(t)} = 1$ if grower k used management i at time t and $I_{ik(t)} = 0$ otherwise.

Let there be a function $N_{ij(t)} = \sum_{K=1}^{1132}(I_{ik(t)}L_{jk(t)})$, which counts the total number of links that grower j has with other growers k that practice management strategy i.

Finally, we define $B_{ij(t)} = \sum_{K=1}^{1132}(P_{k(t)}I_{ik(t)}L_{jk(t)})$, where $P_{k(t)}$ is the yearly profit earned by grower k at time t. $B_{ij(t)}$ gives the profit earned by grower j's linked associates k who practice management level i, at time t.

Growers assess the average of their associates' and their own success for each of the three management levels at each monthly time step. Growers can change which management level they implement within their orchard every 12-time steps based on their observations from the previous year. The figures in **SM 2** provide examples of this process on a smaller data set.

2.2.4. *Disease expansion*

The establishment of a pathogen within an orchard is determined from the epidemic adjacency matrix described in 2.2.2 Epidemic network construction. The probability of preventing both disease establishment and expansion for each orchard is dependent on the management level practiced in the orchard and redrawn at each time step, where the probability of prevention for low, medium, and high management levels is 5%, 40% and 90%, respectively (Evans et al., 2015), where these estimates are described in more detail in **SM 5**. If preventing establishment was not successful, there is a latent period of one month before within-orchard pathogen expansion begins. Within-orchard disease expansion is also a function of the management strategy used. For a low management level, disease expands to 4–8 trees in an orchard; for medium levels, disease spreads to 2–4 trees; for high levels, disease impacts 1–2 trees. If growers were successful at stopping within-orchard expansion, no trees will be impacted at the next time step.

If a grower loses all avocado trees (or available profit, discussed below), the orchard is removed from the epidemic dispersal network the following year, and is not a source of inoculum for disease establishment. This orchard remains in the socioeconomic network and continues to inform grower's perceived benefit for the different management levels.

2.2.5. Costs for management levels

Growers are responsible for covering the costs of their management level at each time step throughout the year (potentially with subsidies through "carrots," discussed more below). Monthly and yearly costs reflect the averaged fees for varying management styles of avocado growers in Homestead; for example, growers practicing "high intensity" management are paying costs at a rate which reflects regular scouting, roguing and applying fungicides, whereas growers practicing "medium intensity" are paying costs at a rate which reflects scouting and moderate levels of roguing. The costs of disease management are in Table 1, where the cost analyses and how these values were determined are described in more depth in **SM 3.**

Every 12 time steps, growers receive a profit based on the number of fruit-producing trees in their orchard and pay the costs for their management level. Growers pay a property tax each year based on the size of their property (in acres), where for simplicity the baseline property tax for all growers is assumed to be 5% of the assessed land value. Florida avocado growers earn on average $1.3 K/acre in profit and lose approximately $51/infected tree(Evans and Nalampang, 2010; Evans, 2018). Prices and profits are fixed over the time frame with regards to the management costs, property taxes and the profit earned from fruit producing trees.

2.2.6. Policy intervention: Carrots and sticks

Carrots in this model are a cost share allocated to growers practicing high or medium management at the start of a realization, designed to reflect the cost share programs implemented in south Florida for avocado growers. Growers can use money from these cost shares to pay 50% of their management costs. The maximum cap on these cost shares varies between realizations, and once the available funds have been used, growers revert to using their own net profit to pay their management costs. Providing growers practicing medium or high management additional funding to cover the costs for maintenance may motivate growers to adopt these higher management levels.

Sticks in this model are imposed when growers practice low management, where growers have a 60% chance of losing their agricultural tax exemption (60% was chosen based on observations of the frequency of land surveys), which increases their yearly property tax of 5% of the assessed land value. The percent property tax increase for these low management growers varies between simulations. Increasing the property taxes on growers practicing low management may incentivize these growers to adopt higher management strategies. This type of stick model was chosen because this type of incentive structure has been proposed for implementation in Homestead, though wealth disparities across growers made the proposal problematic.

Table 1
The costs for management of diseased trees and disease-free trees, and yield loss for three levels of management(Evans et al., 2015; Evans, 2018). Costs for diseased or healthy trees are evaluated each month, and the total number of trees lost throughout the year will result in a yield loss in each new year.

Management	Cost per tree without disease ($/month)	Cost per tree with disease ($/month)	Loss in $ from yield per tree ($/per year)
High Intensity	$1	$20	$51
Medium Intensity	$0.50	$10	$51
Low Intensity	$0	$0	$51

2.2.7. Simulation experiments

We evaluated 400 realizations for each of 299 different parameter combinations, varying the degree of social connections, the pathogen dispersal kernel, the degree of individual's stubbornness, and the carrot and stick parameter values (**SM 4).** The results of the 400 realizations for each parameter combination were averaged to compare the effects of each parameter combination on: (a) the number of healthy avocado trees remaining across the 10-year time-period in each orchard, (b) the average income of each grower, (c) the management level each grower was practicing each year, and (d) the management changes each grower made throughout the 10-year period.

3. Results

3.1. Socioeconomic and epidemic network analyses

We simulated the laurel wilt epidemic across a range of scenarios using two network models, an epidemic network representing the geographic locations of avocado orchards in Homestead, Florida, and a socioeconomic network representing the associations between growers. Our epidemic networks represent the risk of epidemic spread in a gravity model, based on the probability of pathogen movement between two orchards given their geographic proximity, and orchard size (in acres) (Jongejans et al., 2015). We assessed dispersal kernels in the epidemic network across a range of values of $\beta_{epidemic}$, in sensitivity analyses. We represented potential socioeconomic networks using an inverse power law model, which determines the relative likelihood of two growers sharing information with each other as a function of the distance between the two growers and a parameter, and the dispersal kernels in the socioeconomic networks across a range of values of β_{social}., tested across a range of values, and then weighted to reflect the social tendency of affinity, or homophily, in this case the tendency to associate with individuals starting with similar choices for management (Fu et al., 2012). For each realization (consisting of a single, simulated 10-year long laurel wilt epidemic), growers had three different management options to choose from, which were equally and randomly assigned at the beginning of each simulation. Growers could choose a low management level, which would not protect their orchard against disease, but would be free of costs; a medium management level, giving moderate protection against disease with moderate costs; or a high management level, giving the best protection against disease, though comparatively expensive. Growers communicate only with other growers with whom they are linked, learning about their management level and the gross profit earned from using their selected management strategy. Growers decide annually what management strategy they think would be most financially beneficial based on these communications.

A surprising result of the analysis was that the percentage of healthy avocado trees remaining at the end of each realization *decreased* proportionally with the average number of social connections (Fig. 3), where as β_{social} increased, the average number of social connections decreased. The epidemic dispersal kernel determined the rate of pathogen dispersal, where as $\beta_{epidemic}$ decreased, the risk of pathogen dispersal increased; as expected, the percentage of healthy avocado trees increased with increasing $\beta_{epidemic}$. The region fared best in scenarios with both high β_{social} and $\beta_{epidemic}$, or when average socioeconomic network connections were lowest, and the probability of pathogen dispersal was lowest.

Across all simulated scenarios, growers practicing high management had the lowest gross profit per acre, and the growers who were practicing low management and did not go out of business had the highest

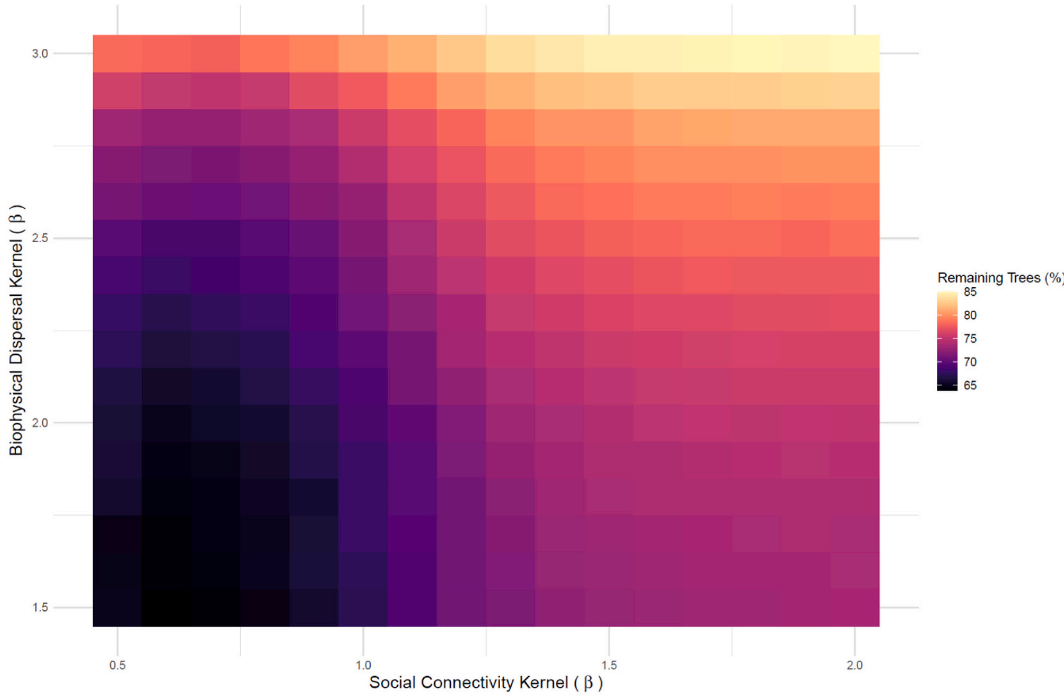

Fig. 3. The percent avocado trees remaining after simulated laurel wilt epidemic scenarios, where darker colors indicate higher mortality rate. Higher values of β for the social connectivity kernel parameter give a decreasing probability of communication, and for the epidemic dispersal kernel give a decreasing probability of epidemic spread. Higher rates of communication (lower β_social valued) resulted in a decrease in regional avocado health.

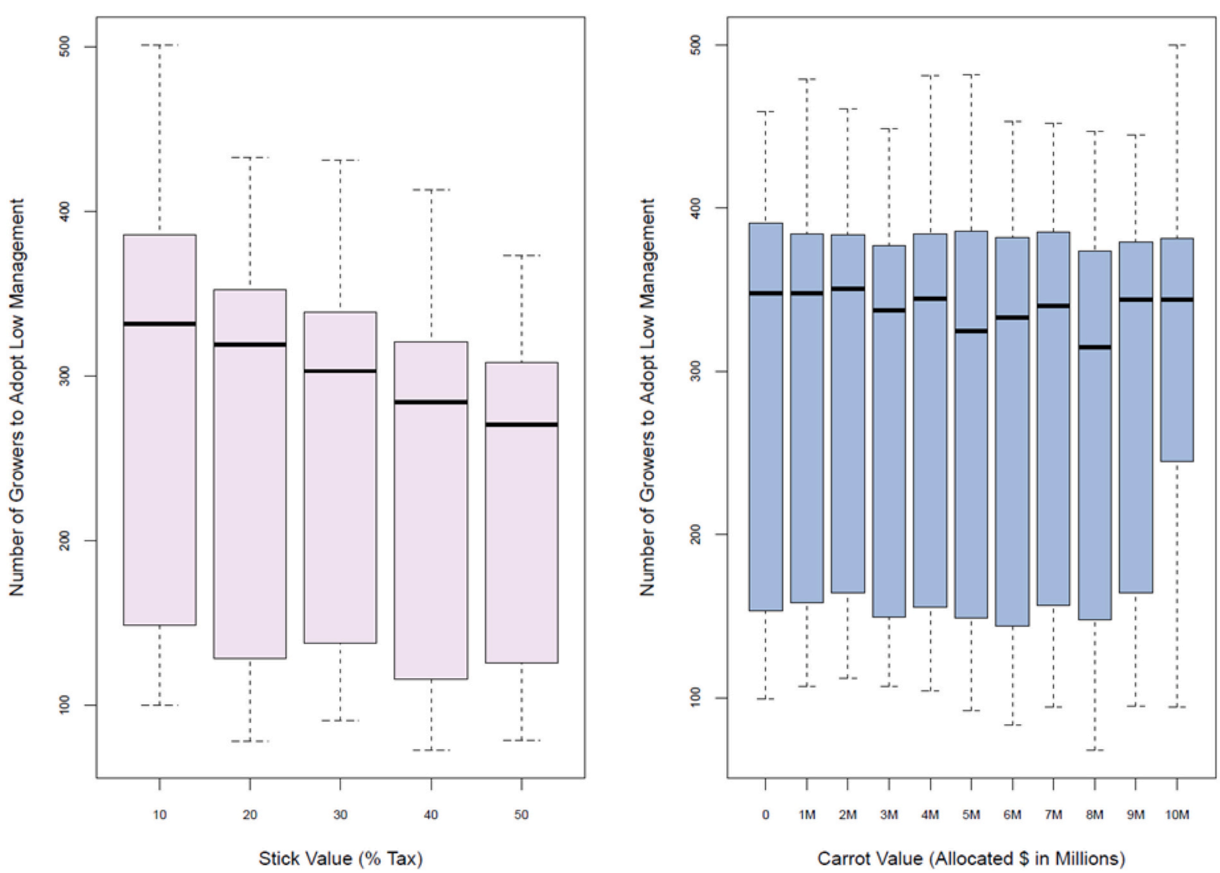

Fig. 4. The total number of growers that adopted low management over a 10-year period A) across increasing property tax values on low management growers (a 'stick' policy), and B) across an increasing amount of money allocated for use by medium and high management growers (a 'carrot' policy).

gross profit. In scenarios with lower β_{social} (higher social connections, on average), growers were more likely to be influenced to change their management level. Across all scenarios, the epidemic progress exhibited biphasic expansion, where the pathogen establishment and dispersal slowly increased linearly within the first five years of the epidemic, and began to increase exponentially, dependent on the value of $\beta_{biophysical}$, for the next five years of the epidemic. More than two-thirds of all avocado tree mortality across a 10-year period occurred within the last five years of an epidemic, disproportionately impacting low-management growers through tree loss and thus, economic instability. In scenarios with higher β_{social}, the second phase of the epidemic did not accelerate as quickly as in scenarios with lower β_{social}. When we compared these results to aerial and ground surveys (**SM5**) in Florida over the last 10 years, comparable rates of expansion to those observed in Florida occurred in computational scenarios where the social and epidemic connectivity of the region fell in $1.1 < \beta_{social} < 2.0$ and $2.2 < \beta_{epidemic} < 2.9$.

3.2. Policy intervention

We tested the effects of policy interventions through carrots – implemented in this model as a lump sum of money given only to growers practicing a medium or high management level, to cover half of their management costs – and through sticks, implemented as a property tax increase for low management growers. Carrots alone had no effects on influencing low management growers to adopt high or medium management levels across a 10-year period. Carrots did slightly increase the average net profit per acre of growers practicing medium and high management. The sticks alone decreased the number of growers who practiced low management proportionally to the increasing property tax value (Fig. 4a). For example, in scenarios where low management level growers paid a 10% property tax on their assessed land value, on average 290 growers (25% of growers in the region) were influenced to adopt low management over the 10-year period. In scenarios where low management growers paid a 50% property tax, on average 230 growers (20% of growers in the region) were influenced to adopt a low management level over the 10-year period. The region fared best when policy strategies applied both high carrot and stick values, where increasing stick and carrot values together decreased adoption of low management levels and increased adoption of medium and high management levels.

3.3. Stubbornness

Lastly, we tested the effects of social behaviors on regional health through stubbornness. Each grower was assigned a level of stubbornness where growers with a lower stubbornness would more likely be influenced by the information they receive in their socioeconomic networks. In scenarios where growers had a lower stubbornness, and so were more likely to change their management level based on the information obtained from their social network, regional health was lower on average. The region fared best when growers were the most hesitant to adopt a different management level, or had high stubbornness. When growers were more hesitant to use new information, a higher percentage of growers chose to maintain high and medium levels of management, whereas when stubbornness was low, more growers chose to adopt the low-level management. In scenarios with high stubbornness, the acceleration of epidemic expansion during the second phase of the 10-year epidemic was dampened and the region fared best. For example, when growers were the most hesitant to adopt a different management level, 71% of avocado trees remained healthy (613 K trees) on average, compared to when individuals were the least hesitant, where on average 69% of the avocado trees remained healthy (604 K trees).

4. Discussion

4.1. Socioeconomic and epidemic networks

In this study, we simulated the patterns of laurel wilt disease expansion and information exchange to address three attributes of an epidemic: i) pathogen dispersal and socioeconomic influence, ii) the effects of carrot and stick policies on influencing collective action, and iii) how an individual's level of stubbornness towards new information may affect regional health. Here we discuss the outcomes from this model, the implications of the outcomes, and the model design aspects which contributed to these outcomes. In scenarios where the average number of social connections within socioeconomic networks was higher, there were fewer avocado trees remaining at the end of a 10-year period when compared to socioeconomic networks with fewer social connections. This counterintuitive result indicates that, in these scenarios, when growers have more sources of information from other growers, the region fares worse. The increase in information sources raises the likelihood of growers adopting low management levels, if growers are communicating with a wider range of individuals (Fig. 5). Given that low management growers are paying no costs to manage their orchard (except yearly property taxes), in these scenarios, they have a high influence on their neighbors' perception of the low management level's benefit, despite the associated risk of disease establishment and expansion. Epidemic expansion was relatively slow in the first five years, or the lag phase of the epidemic. Growers practicing a low management level can accrue profit during this lag phase, whereas growers practicing medium and high management levels pay costs to protect their orchard, even while the rate of disease expansion is slow and before disease reaches their orchards. This is likely why we see a dramatic shift in growers that adopt a low management level during the lag phase of these simulations: many low management growers have not yet been impacted by disease *and* are paying no costs to protect their orchards against disease. Decision support systems can be designed to address these issues; for example, the Integrated Aerobiology Modeling System was developed to forecast soybean rust spread and to reduce pesticide applications in regions where the pathogen was not yet present during periods of slow disease expansion (Isard et al., 2007). When growers only share information about their net profit and their management strategy, the lowest management level is the most persuasive. Future scenario analyses could include growers weighting tree loss in addition to profit in their decision making, as this would likely change the outcomes of these scenarios analyses. Growers in Homestead communicate with their neighbors about not only the economics of laurel wilt management, but their success; these growers are able to directly observe the management outcomes of their associates, which heavily impacts their decision making. Community management of infectious disease, and biological invasions more generally, illustrates the "tragedy of the commons," how the pursuit of self-preservation can inhibit the adoption of innovations needed to achieve sustainable practices (Clark and Harley, n.d.; Clark and Harley, 2020; Isard et al., 2007). In the case of the laurel wilt epidemic, it may be financially beneficial for a grower *not* to manage for laurel wilt, at least in the short run, under the assumption that their neighbors are all managing for laurel wilt; the caveat for individuals deciding against management is that the risk for disease is still present, though lower. This model is designed to consider these potential tragedies, as disease expansion is spatially dependent; if an individual grower's nearest neighbors are all managing for laurel wilt, the individual may not need to manage. In an ideal scenario, if all growers were heavily managing for laurel wilt, they would eradicate the disease, thus reaping the benefits of collective action. Unfortunately, *H. lauricola* has a wide range of other available hosts, so eradication is unlikely.

After the lag phase of the epidemic, we see a dramatic increase in disease expansion and establishment, or the beginning of an acceleration phase. Low management growers are most impacted by this shift, as their orchards are not protected against disease; most low management

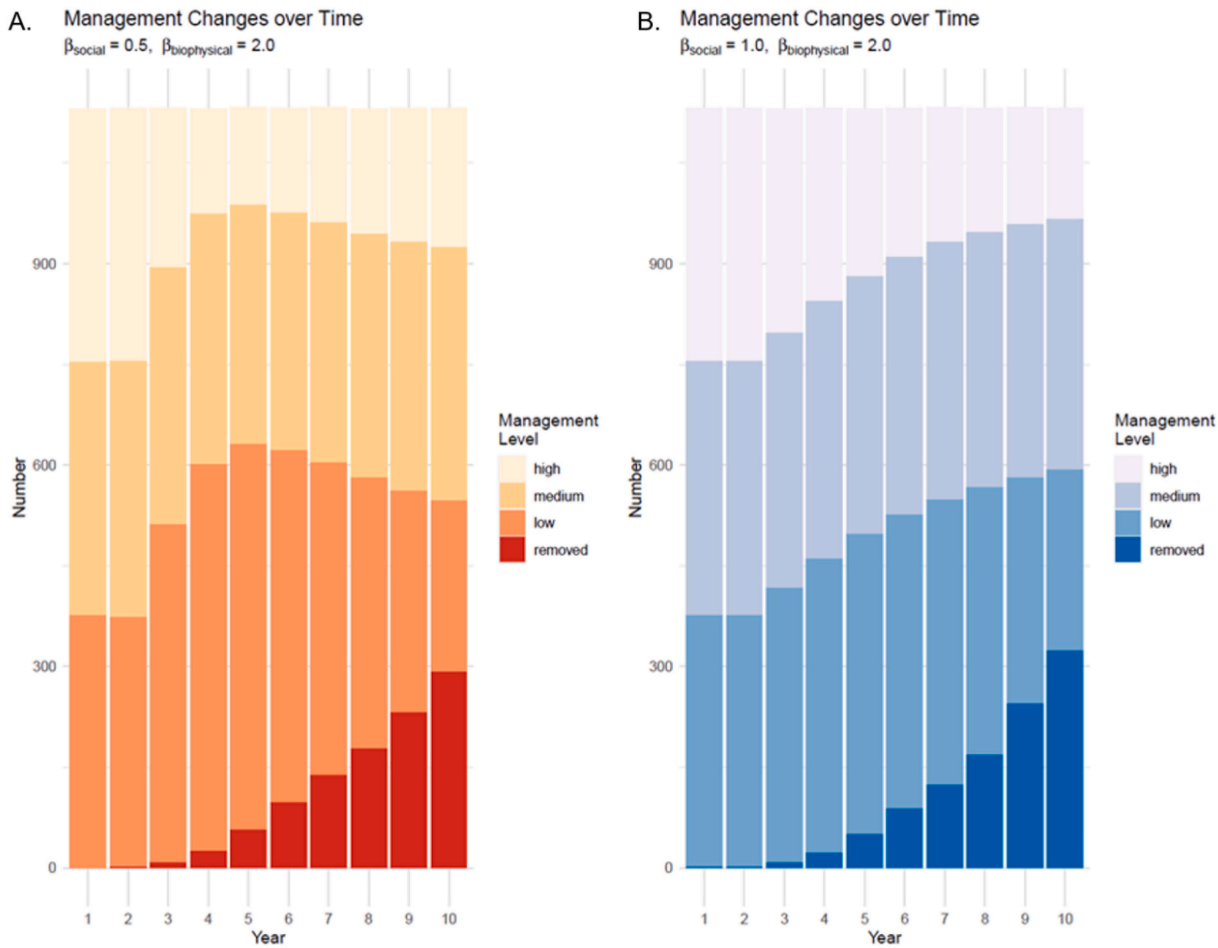

Fig. 5. The number of growers over time practicing a high, medium, or low disease management strategy, or being removed because of financial losses or tree death, for a biophysical (or epidemic) β = 2.0, and A) a social β = 0.5, and B) social β = 1.0. Higher social β results in less communication. For higher communication scenarios (A), the number of growers choosing low management rises substantially in the early phase of the epidemic.

growers cannot maintain economic viability when disease expansion intensifies, as a majority of their trees are lost to disease. It is necessary to mitigate the number of individuals who practice low management during the lag phase of the epidemic, as these individuals increase regional management rejection, and thus, reduce regional health during the acceleration phase of an epidemic. This mitigation, though, will be hampered by the pursuit of self-preservation, thus informed agitation becomes necessary for the security of food systems. Informed agitation and the awareness of increasing disease risk comes from actors like extension specialists, stakeholders, institutional bodies, and policy-makers within a community, who are critical for shaping collective action towards more effective management techniques during the initial phase of an epidemic, and as the population dynamics of an epidemic continues to shift (Bagnoli et al., 2007; Clark and Harley, 2020; Poletti et al., 2012). In the scenarios studied here, it is important to note that there are no external sources of technical information, and growers relied only on the casual information obtained their neighbors. This absence of informed agitators in these simulations shows how a food system may operate without intervention: self-preservation or financial gain persuades a large majority without an understanding of the impact their actions will have. Direct comparison of systems with or without informed agitators can quantify their regional impact. For example, Dowd et al. (2014) found that agricultural networks with weaker social support ties (or passive information consumption) and stronger ties to knowledge (or proactive information consumption) were more effective in transforming the actions of individuals. In networks with increased social connections and minimal informed or knowledgeable connections, individuals and informed agitators must proactively create knowledgeable connections, particularly during the lag phase of an epidemic, where the actions of an individual can be most impactful. Future model applications could also incorporate informed agitators who influence the dynamics of information exchange, as this would also greatly change the outcomes of social interactions.

It is important to consider which aspects of the results are likely direct outcomes of the design choices in construction of the agent-based model. Information exchange is counterintuitively found to be harmful to the avocado industry in these scenarios, though this could potentially be reversed in scenarios where management was less expensive and more effective. It may be hard to avoid regional management problems during the lag phase of epidemics, when few orchards are infected and avoiding management expenses can benefit growers in the short run. Our results are also specific to the laurel wilt epidemic in Homestead, Florida. The laurel wilt epidemic in these scenarios is strongly dependent on social proximity, and given the limited area (~8500 acres) and clustering of orchards within Homestead (across ~14 mile^2), social and epidemic connections are more likely to occur. In avocado production regions that are larger or randomly dispersed across a region, long distance disease dispersal and social connections would be less likely to occur when associativity decays with distance. For avocado production in regions like California, which has more production region (~50,000 acres) spanning from San Diego to San Luis Obispo, pairwise social and epidemic connections will be less likely to occur across the entire production region. In larger regions like California, we may expect laurel wilt outbreaks and social connections to be clustered, and management options to differ in efficacy across the region (Buddenhagen, 2022). Scenario analyses using agent-based models such as this can be used to evaluate regional management strategies for new types of landscapes.

4.2. Carrot and stick policy incentives

Collective action is often inaccessible to many individuals, given the high costs of some sustainable practices. For example, in huanglongbing management in Florida citrus, collective action was difficult due to the financial constraints of growers and the lack of successfully implemented top-down regulations (Clark and Harley, 2020; Costa, 2021; Singerman and Rogers, 2020). Our next goal in this study was to observe how policymakers can influence decision making by addressing the equity of more sustainable management efforts. We evaluated carrot and stick policies, where growers are rewarded for beneficial management and penalized for detrimental management strategies, respectively. We found that sticks were more successful in influencing regional decisions; the higher the penalty for low management growers, the less likely the region was to adopt low management. Conversely, we found that carrots alone had no effect on influencing regional decision making; when used in combination with sticks, though, carrots helped to influence growers to adopt higher management levels. These results are supported by economic studies on the effects of carrots and sticks, for example, Andreoni et al. (2003) and Costa (2021) found that carrots were less effective in motivating individuals to respond selfishly in a series of payoff games, or in adopting sustainable initiatives, respectively, whereas sticks helped to increase group cooperation; the combination of both carrots and sticks resulted in the greatest benefit for the entire group.

In our study, it is likely carrots did not influence decision making due to the low cost of the low management level. Although the carrot (funds for growers to use) covered half the costs for medium and high management growers with disease in their orchard, choosing low management was still the least expensive option. In addition, in these scenarios the funds were only available to growers who had disease present, and use of high management rendered disease establishment less likely, reducing the use of these funds for many growers. These simulations also did not provide growers with the knowledge that carrots and sticks were implemented; growers could only observe the effects of these policy incentive structures through the income fluctuations of their associates. In some cases, foreknowledge of potential loss of an agricultural exemption for taxes would be enough to motivate growers to avoid selecting a lower management strategy. Observations in Homestead provide additional perspectives on the use of carrots in practice. Carrots did have a positive impact on growers in Homestead by helping them replant avocado trees and remove dead trees, and the benefits were available to all growers in the region and not only to growers practicing a moderate or higher level of management. Future simulations should explore a wider range of carrots, and the use of more complete subsidies for growers practicing high management, even before disease is present.

4.3. Stubbornness

Growers differ in their management choices, particularly in cases where the management strategies are expensive and/or time consuming. The likelihood of implementing new management efforts, or reducing management efforts, may also depend on the tendency for an individual to display stubbornness. The concept of "stubbornness" has been widely studied in evaluations of group behavior theory (Ghaderi and Srikant, 2013; Ghaderi and Srikant, 2014; Li et al., 2017; Yin et al., 2019; Zhou and Wu, 2022); for example, Ghaderi and Srikant (2013) studied how opinions and group consensus may be dependent on the distribution of stubborn individuals. Our final goal was to observe the effects of social tendencies like stubbornness on regional health. In one extreme, we have low stubbornness, which can be seen as irresoluteness towards previous decisions, generally having a positive outlook on new information (if financially viable). In the other extreme, we have high stubbornness, which can be seen as steadfastness towards previous decisions, generally giving a lower weight to new information, despite persuasive evidence. For example, in Homestead some growers have chosen to stump their trees (removing the above-ground portion of the tree) despite information encouraging them to rogue trees (removing the entire tree, including the roots), if they have a higher stubbornness (Ploetz et al., 2017a; Ploetz et al., 2017b). A lower or higher stubbornness has many socioeconomic and cultural influences (e.g., age, gender, education, capital, etc.), though regardless of the reasons for an individual's level of stubbornness, their decisions about when and how to implement management efforts has the potential to change the outcome of an epidemic. In these models, individuals can be perfectly impartial (having no bias towards new information whatsoever), although in reality, most individuals will fall somewhere between the two extremes of strong positive or negative bias.

As bias against acting on new information increased (an individual's stubbornness increased), the probability of a grower changing their management strategy decreased, and the regional health surprisingly increased. This is likely due to the allure of low management: low management growers in the lag phase of the epidemic are paying little costs and are not yet affected by disease, persuading many in the region to also adopt low management. Where treatment options are optional, free riding problems arise, where individuals rely on their neighbors to manage for disease (Singerman and Rogers, 2020; Wang et al., 2020). In scenarios where growers are more hesitant and have higher stubbornness against adopting new management efforts, growers are less likely to be persuaded by the allure of changing to low management. Although stubbornness against new information can be seen as a harmful attitude in some situations, in these scenarios, it is this refusal to change to a lower management effort which can save the region from laurel wilt. Ghaderi and Srikant (2013) describe how, in the presence of individuals with higher stubbornness, a group may not converge towards one decision, but an equilibrium will develop; in the case of laurel wilt, this equilibrium is influenced by the growers practicing high management, as these growers maintain high management and persist across the epidemic. Public goods games have sought to address similar scenarios and how best to avoid free rider problems to achieve herd immunity. For example, Fukuda and Tanimoto (2015) found that during an epidemic, individuals who will always get vaccinated have a greater social influence than individuals who will never get vaccinated. Similarly, Wang et al. (2020) found that individuals who are motivated to get vaccinated can greatly benefit a region, even when regional conformity motivates individuals to remain unvaccinated. "Stubborn" individuals who refuse to adopt low management or insist on getting vaccinated, not only benefit the health of the region, but in the long term, are able to socially influence others through their own success and health (Wang et al., 2020). These individuals who refuse low management, help to increase herd immunity levels, and these individuals are especially valuable during the lag phase of an epidemic, where the visible cost of disease is much lower than the visible cost of management. In our model, we assumed that an individual's stubbornness was a fixed, constant value across time, which is a simplification; Zhou and Wu (2022) studied opinion dynamics where individuals' stubbornness levels evolve over time, and found that a group opinion would be reached when there are fewer stubborn individuals and higher social connectivity. As more evidence is presented through informed agitation by thought leaders, or as the epidemic enters a new phase, even the most stubborn of individuals might be persuaded to pursue a more effective and sustainable management effort.

The effects of stubbornness are also heavily dependent on the structure of the social network, where growers are connected with other growers within a closer spatial proximity, and weighted to reflect homophily in management choices. In these scenarios, a weight of 0.4 was chosen to reflect the tendency of growers to prefer communicating with like-minded individuals in Homestead. Future models could consider the effects of these scenarios across variable homophily weights. With a higher weight (>0.4), regional homophily would be higher, and clusters of social networks would form among like-minded growers. The effects of stubbornness in scenarios with higher homophily weights would be less impactful, given information exchange would already be driven by the formation of homophilic clusters.

5. Conclusion

These scenario analyses show how important informal information exchange can be in systems like the laurel wilt epidemic, and the challenges of collective management of epidemics and invasions more generally. To meet these challenges, stakeholders must evaluate management options and regional knowledge about management options across epidemic phase shifts. Extension agents and other educators must continue to create ties within socioeconomic networks to inform about disease risk and when is best to protect against disease. Here we incorporate the effects of an individual's stubbornness, the effects of carrot and stick policies, and how these facets of an epidemic influence the management decisions of growers during an epidemic. Growers face a continually shifting market when making their management decisions and optimizing investments for disease management can aid in regional economic viability and food security. Although the Florida avocado industry has experienced a loss in the total bushels of avocado sold, the price paid per bushel has increased recently, leaving avocado producers financially better off than in previous years and unable to meet the production demand. Laurel wilt has the potential to spread to new regions like California, Mexico, and Hawaii, and understanding how information exchange influences decision-making in current scenarios for epidemics will be a key step towards achieving collective action for sustainable health management and the security of food systems.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Code is available at https://github.com/bereaetherton/Laurel-Wilt-Agent-Based-Model-

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Appendix A. Supplementary data

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