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Analysis

Public policy for management of forest pests within an ownership mosaic

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ABSTRACT

Urban forests provide ecosystem services that are public goods with local (shade) to global (carbon sequestration) benefits and occur on both public and private lands. Thus, incentives for private tree owners to invest in tree care may fall short of those of a public forest manager aiming to optimize ecosystem service benefits for society. The management of a forest pest provides a salient focus area because pests threaten public goods provision and pest management generates feedback that mitigates future risks to forests. We use a game theoretic model to determine optimal pest treatment subsidies for a focal privately owned tree and use an optimization approach to guide targeted public treatment of a representative public tree. We find that optimal public subsidies for private tree treatment depend on assessed tree health and on the prevalence of the pest in the community, considerations absent from many existing programs. Next, by applying our pest treatment policies to a community-scale model of emerald ash borer forest pest dynamics, we predict ash mortality under a range of treatment scenarios over a 50-year time horizon. Our results highlight how designing policies that consider the public goods benefits of private actions can contribute to sustainable land management.

The UN's 2030 Agenda for Sustainable Development defines a set of interconnected global goals, including transitioning toward cities that are resilient and green (United Nations, 2015). Realizing this objectives will require major investments by governments, companies, and individuals (Sachs et al., 2019). The crux of spurring sustainability transitions, especially in urban areas, is that the benefits of individual investments often accrue at broad scales and to many people. In other words, there are public goods problems embedded within many potential sustainability solutions and private incentives for action will often fall short (Olson, 1965; Bergstrom et al., 1986).

This challenge arises in many contexts, including urban forest management. Urban forests, comprised of the public and private trees within urban areas, contain 5.5 billion trees in the US (Nowak and Greenfield, 2018). These forests provide myriad ecosystem services, including carbon sequestration, erosion mitigation, and cooling, which provide benefits to the over 80% of Americans who live in urban areas (Dwyer et al., 1992; Roy et al., 2012; Livesley et al., 2016; Pataki et al., 2021). However, in the US a minority of urban trees are publicly owned, with these mainly found in parks and rights-of-way bordering streets (Arbor Day Foundation, 2018). As a result, urban forests are a complex mosaic of public and private lands managed by numerous individuals (Dwyer et al., 2003; Epanchin-Niell et al., 2010). Since the ecosystem service benefits of these forests spillover across ownerships, the investments needed to sustain urban forests are impure public goods. Thus, in the absence of appropriate policies, under-investment in stewardship on private land is expected (Wichman, 2016). Public subsidy and cost-share programs (Andreoni and Bergstrom, 1996; Chizmar et al., 2021) are tools that can boost private provisioning of public goods, yet it remains a challenge for policy makers to design cost effective programs (Jacobsen et al., 2017; Chan and Dinelli, 2020). Moving toward cities that are sustainable, resilient, and green may benefit from carefully designed public policies that support individuals in taking actions that collectively contribute to sustainability.

The United States' Inflation Reduction Act of 2022 is making sustainability and climate mitigation investments (Bistline et al., 2023), including through a USDA Forest Service grant program that supports tree planting and care on both public and private lands (USDA Forest Service, 2023b). For example, the Pittsburgh Canopy Alliance received $8 million to plant and maintain trees along streets, in parks and public green spaces, and in residential and institutional property in neighborhoods where investments in greening will contribute to social justice (USDA Forest Service, 2023a). The city of Minneapolis received an $8 million grant for treatments to protect ash trees (*Fraxinus spp.*) from emerald ash borer (*Agrilus planipennis*)(henceforth referred to as EAB) as well as removal of infested ash trees and replanting of diverse tree species (City of Minneapolis, 2023). Both approaches could contribute to more resilient future forests and more sustainable cities. We focus on the case of forest pest management, as it bears many of the hallmarks of the broader challenge of designing policies to promote

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sustainability on intermingled public and private lands. At the same time, given the unprecedented funding for urban forestry under the Inflation Reduction Act, it is especially salient to determine polices that could cost-effectively sustain urban forests in the face of threats from pests.

The management of forest pests adds additional complexity to the general problem of spurring private contributions to public goods because each individual's control decisions affect not only the impact of the pest (or disease) on a focal tree but also it is spread across the landscape. For example, insecticide treatments, such as trunk injections with emamectin benzoate, provide effective EAB control to treated ash trees (McCullough et al., 2011) and also mitigate the risk of infestation of neighboring trees (McCullough and Mercader, 2012). This spillover effect results in a spatial-dynamic externality (Wilen, 2007) that has been studied in the context of pest spread (Epanchin-Niell and Wilen, 2015), including within management mosaics (Sims et al., 2010; Kovacs et al., 2014). A spatially-explicit game theoretic analysis of the control of a mobile renewable resource with harmful local effects (such as a forest pest) has shown that decentralized management by individuals often diverges from socially optimal control policies, especially when the damages caused by the resource are intermediate (Costello et al., 2017). In these cases, there may be a role for public policies that stimulate increased private investment in management. Subsidies and transfer payments are often proposed as mechanisms to align public and private incentives for pest management in urban forests. For example, Chen et al. (2023) use a principal–agent modeling framework to design programs in which a local government reimburses landowners for pest management costs based on numbers of infested or treated trees on the property. Cobourn et al. (2019) show that transfer payments between municipalities can induce levels of pest control that make each city better off and approach a central planner's goal of maximizing net social benefit.

Existing management policies for forests pests such as emerald ash borer embody some of these features. State and local governments have developed plans for managing ash trees on public land (i.e., along roads and in parks). These plans include ash tree inventory, monitoring, removal, and insecticide treatment, reforestation and outreach (e.g., City of Saint Paul, 2022). Management plans also include guidelines for homeowners with ash trees in their yards (e.g., Purdue University Emerald Ash Borer Decision Guide (Nagle and Sadof, 2018), Minnesota DNR guidelines for homeowners with ash trees,[1] and City of Saint Paul guidelines for homeowners with ash trees[2]). These guidelines focus on the homeowner's decision to either treat or remove their trees based on the trees' health and the owners' management objective (i.e., whether they are interested in maintaining the crown cover in their yard and can afford the cost of treatment). These guidelines for homeowners who have ash trees in their yards do not discuss the public good of maintaining ash tree cover in their neighborhood or slowing the spread of EAB to neighboring trees. Nevertheless, some cities do offer homeowners incentives to treat their ash trees in the form of discounted prices for insecticide treatment (e.g., City of Burnsville, 2015), which suggests interest in maintaining the public benefits tree cover regardless of ownership. More widespread adoption of such programs may be limited by key sources of uncertainty that diminish public managers' confidence in establishing programs to support pest treatment by private tree owners. Our work incorporates critical details about ownership type, key uncertainties about tree health, community infestation state, and tree owners willingness to pay for treatments. As a result, we are able to derive more precise and cost-effective policies that can help slow the spread of a pest and maintain the value of tree cover at community scales. Our findings present opportunities to refine existing programs or establish new ones, with the potential for more effective and efficient management of forest pests.

We address the general challenge posed by forest pests to municipal forest managers in urban environments by considering three interrelated questions. First, how can public subsidy programs be designed to efficiently spur investments in forest pest management on private lands? Second, what are the optimal pest treatment decisions for publicly owned trees? Lastly, in a mosaic landscape of public and private lands, how effective are these policies at mitigating pest spread and maintaining forest health over time? These issues are made more complex because of numerous uncertainties facing both private and public decision makers, which we address.

To address the first question, we construct a game theoretic model of subsidy policies for treatments to address forest pests on a focal privately owned tree, assuming that tree owners are myopic and consider only short-term costs and benefits over the duration of efficacy of treatment. To address the second question, we deploy an optimization approach to study treatment decisions for a focal public tree. Shifting from a static to dynamic perspective, we answer the third question via the development of an epidemiological model of the dynamics of pest spread and tree mortality over many decades. This model integrates the impacts of treatment of public and private trees in scenarios corresponding to the outputs of the initial models. We then explore the application of these three approaches in a case study of the management of EAB in an urban mosaic of public and private land. Our model is relevant to cities with EAB management plans (e.g. City of Burnsville, 2015) that might benefit from refinements in how they strategically treat their publicly owned trees and how they encourage treatment of private trees.

We find that optimal subsidy levels for private trees are dependent on tree health and how widespread a forest pest is within a community, considerations which are absent from many existing treatment programs. For EAB, comparing predicted long-term tree survival under scenarios where there is no public action to treat a pest and where optimal treatment policies are deployed across public and private ownership shows how these lands interact to shape collective risks to forest health. Our approach provides a road map for the design of public policies that aim to stimulate collaborative pest management in an ownership mosaic.

1. Treatment subsidies for private trees

We construct a game theoretic model of the treatment of a single tree growing on private land that is susceptible to a forest pest that can be managed with treatments administered by a tree care specialist. The model considers strategic interactions between two stakeholders: a municipal forester and a tree owner. The municipal forester offers pest treatment subsidies for the care of private trees with an objective of optimizing forest ecosystem service benefits subject to the cost of the subsidy policy. The private tree owner makes a decision whether or not to treat their tree with the objective to maximize the benefits they receive from their tree, taking into account treatment costs. Henceforth, we call these stakeholders the municipality and the tree owner. A game theoretic approach is necessary because the objectives of each stakeholder are interdependent. This approach allows us to consider uncertainty that the municipality may have about the tree owner and incorporate this into the design of the subsidy program.

The structure of the model is shown in Fig. 1. Beginning with a focal tree that falls into one of three pest infestation states (healthy, infested, or dying/dead), the state of the tree is (imperfectly) assessed based on observable characteristics. For example, in the context of EAB management, arborists can assess ash tree health by observing the tree's crown condition, which is correlated with infestation (Flower et al., 2013; Knight et al., 2014). However, an ash tree with no visible crown dieback may have either no infestation or a low level of infestation that

[1] https://www.dnr.state.mn.us/invasives/terrestrialanimals/eab/management.html: accessed 3/3/2025.

[2] https://www.stpaul.gov/departments/parks-and-recreation/natural-resources/forestry/emerald-ash-borer/homeowners-guide: accessed 3/3/2025.

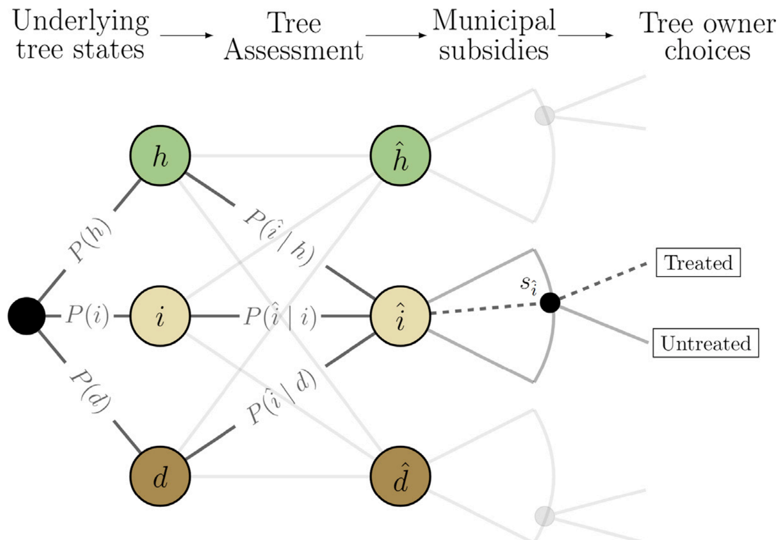

Fig. 1. The structure of the game theoretic model, from assessment of a tree's health to treatment outcomes. A focal tree can fall into one of three states (healthy, h; infested, i; dead/dying, d) with likelihoods given by community level forest pest prevalence. Next, the health status of the tree is assessed (assessed as healthy, $\hat{h}$; infested, $\hat{i}$; dead/dying, $\hat{d}$), with assessment errors possible. This splits the game into three branches, one for each assessed tree state. The game that follows for each assessed health state can be analyzed independently. We highlight the case of a tree that has been assessed as being in an infested state. The municipality sets a subsidy level that reduces the cost of treatment for a tree owner and the tree owner responds to this in their decision to treat their tree or not. The arc in the figure represents the continuous range of subsidy levels that the municipality can set. Here we show a case where the subsidy is high enough that the tree owner decides to have their tree treated.

has yet to cause visible damage. Conversely, crown dieback observed in a ash tree could be due to a different cause. Similar assessment inaccuracies are likely to arise in the context of other forest pests and diseases. We define assessment accuracy probabilities that allow the stakeholders to estimate the likelihood of each underlying tree health state using Bayes' theorem.

For each possible assessed tree health state, we analyze municipally subsidized treatment of a privately owned ash tree as a dynamic game of incomplete information. This allows us to consider subsidy policies that vary for different tree health states. Fig. 1 highlights the structure of the game for a tree that is assessed as infested. In this case, the municipality selects a non-negative subsidy level that partially offsets the costs of treatment for a tree owner. In response to the subsidy level available and the price of treatment, the tree owner decides whether to treat their tree or not. The tree owner has a unique 'type' which we define as the value that they assign to avoiding tree mortality over the period of efficacy of the treatment. While the tree owner knows this value, the municipality only knows the distribution from which this value is drawn. This introduces incomplete information for the municipality. Therefore, we assume that the municipality aims to maximize their expected utility given their beliefs about the distribution of tree owner values. These assumptions allow us to solve for the Perfect Bayesian Equilibrium (a refinement of the Nash equilibrium) of the game. Most analyses of Perfect Bayesian Equilibria concern how actions reveal information about a players type. Our analysis is greatly simplified because the tree owner (the player about whom there is incomplete information) makes the final decision in our model and therefore any information revelation cannot impact the municipality's strategy.

We proceed to introduce key aspects of tree health assessment, treatment effectiveness, and treatment dependent tree mortality risk perception that underlie the (expected) payoffs of the tree owner and the municipality. Then we will derive the benefits of treatment from the perspectives of the tree owner and municipality. Using these benefits, we construct the objective functions of each player in the game, and describe how this game can be analyzed. Finally, we define the optimal subsidy policy and resulting treatment outcomes for a representative privately owned tree.

Tree health assessment. We assume an arborist assesses the health status of a tree as healthy, $\hat{h}$, infested, $\hat{i}$, or dead/dying, $\hat{d}$, with an arbitrary assessed state denoted $\hat{\phi} \in \{\hat{h}, \hat{i}, \hat{d}\}$. A tree's health status is only partially observable, with the true underlying state $\phi \in \{h, i, d\}$ of the tree possibly diverging from the assessed state. We assume that surveillance data are available at the municipality scale, with publicly known frequencies of each underlying tree state given by $P(h)$, $P(i)$, and $P(d)$. Since assessment techniques are imperfect predictors of the true underlying health of a tree, we define the accuracy of assessment with probabilities. For example, $P(\hat{h} \mid i)$ is the probability that a tree is assessed as healthy given that it actually is infested. There are nine of these probabilities, which can, in general, be written as $P(\hat{\phi} \mid \phi)$ for some assessed state, $\hat{\phi}$, and some true underlying state, ϕ.

When a tree owner is deciding whether to treat their tree and when the municipality is setting subsidy policies for trees, they use the information in the assessment of the tree's health to update their beliefs about the likelihood of the tree having each of the three possible underlying states using Bayes' theorem. These probabilities can be written as $P(\phi \mid \hat{\phi})$ for some true underlying state, ϕ, given some assessed state, $\hat{\phi}$, and calculating these probabilities relies on the publicly-known community-level prevalence of healthy, infested and dying trees as well as the accuracy of assessment.

Effectiveness of treatment. Two pathways of treatment effects are considered. First, a healthy tree's risk of infestation given exposure to a forest pest may be reduced by treatment. This is akin to vaccination of the tree. We define ϵ_h as the effectiveness of treatment at preventing establishment of infestation with a pest (in other words, treatment effectiveness for healthy trees, hence the h subscript). At one extreme, if $\epsilon_h = 1$ the treatment is 100% effective and there will be no chance of infestation over the time horizon of effectiveness of treatment, conversely if $\epsilon_h = 0$ then treatment will have no impact on the infestation risk of a healthy tree. The second pathway of treatment impact that we consider is the potential for treatment of an infested tree to reverse the infestation and return the tree to a healthy state. We define ϵ_i as the effectiveness of treatment for an infested tree and it represents the likelihood of tree recovery given treatment (in other words, treatment effectiveness for infested trees, hence the i subscript).

Perceived tree mortality risks. We assume that the municipality and the tree owner form risk perceptions about the likelihood of tree mortality over a fixed time horizon and employ these risk assessments in decision making. The decisions of the municipality and the tree owner influence the direct risk of mortality (or conversely, likelihood of survival) for a focal tree. Their decisions can also have spillover effects on the spread of a pest within a community and thus influence mortality risks for non-focal trees. We assume that a private tree owner considers only the direct impacts of their actions, whereas the municipality considers both direct and spillover effects because they are aiming to optimize forest ecosystem service benefits at a broad scale. We develop estimates for the perceived direct and spillover impacts of treatment and non-treatment by drawing on epidemiological models.

We assume risk perception is formed via forecasting a tree's mortality probability given current infestation levels remain constant over the time horizon of treatment efficacy. This forecast will typically diverge from realized mortality risks over time because of the assumption that infestation levels remain constant, however, this simplification results in an analytically tractable epidemiological model from which equations for the risk of mortality over time under treatment or non-treatment are derived (see Supplementary Material Section B.4 for a complete description of the risk perception model). We define $\mu_{t\phi}$ as the perceived mortality probability for a treated tree (throughout the manuscript, a 't' subscript corresponds to 'treated') in health state ϕ over a time horizon τ^* which corresponds the to duration of efficacy of treatment. Similarly, we define $\mu_{u\phi}$ as the perceived mortality probability for an untreated tree (throughout the manuscript, a 'u' subscript corresponds to 'untreated') in health state ϕ over the same time horizon.

In addition to the direct impact of treatment on the survival of a focal tree, by eliminating a source of pest spread the treatment can also affect other trees in the community, resulting in a dynamic externality (Wilen, 2007). We model these potential spillover effects of treatment by drawing on the effective reproduction number in epidemiology which defines the expected number of secondary infections caused by a single infection. In the context of forest pest management, this represents the expected number of newly infested trees attributable to a focal tree, which can depend on treatment. For example, healthy trees that are treated are less likely to become infested and therefore less likely to cause mortality of other trees. Similarly, an infested tree that is treated may recover and reduce the expected spillover mortality risk. Using this approach, we estimate spillover tree mortality risk under treatment and non-treatment (see Supplementary Material Section B.5 for a complete description of the spillover risk perception model). We define $\lambda_{t\phi}$ as the perceived spillover mortality risk (expected number of trees in the community that will experience mortality due to the focal tree) for a treated tree in health state ϕ. We similarly define $\lambda_{u\phi}$ as the perceived spillover mortality risk for an untreated tree. In our model, private tree owners ignore spillover mortality risk when making treatment decisions because this spillover is an externality from the perspective of a private tree owner. However, from the perspective of the municipality, this spillover risk is central because it estimates how both public and private treatment influences community tree survival.

Value of treatment. In our model a tree owner makes decisions by comparing the costs and benefits of two alternative outcomes: tree survival versus tree mortality. We assume that the value of a surviving tree to its owner is V_o and that the cost associated with tree mortality, such as removal costs, is W_o for the owner. Throughout the manuscript, 'o' subscripts denote terms that correspond to the owner of a private tree. We assume V_o and W_o are assessed over a time horizon that corresponds to the length of effectiveness of treatment. The likelihoods of survival versus mortality and the assessed state of the tree define the payoff to a tree owner (ignoring treatment costs) of having a treated or untreated tree. These payoffs are

$$\pi_{t\hat{\phi}} = P(h \mid \hat{\phi}) \left(\left(1 - \mu_{th}\right) V_o - \mu_{th} W_o \right) + P(i \mid \hat{\phi}) \left(\left(1 - \mu_{ti}\right) V_o - \mu_{ti} W_o \right) - P(d \mid \hat{\phi}) W_o \quad (1)$$

$$\pi_{u\hat{\phi}} = P(h \mid \hat{\phi}) \left(\left(1 - \mu_{uh}\right) V_o - \mu_{uh} W_o \right) + P(i \mid \hat{\phi}) \left(\left(1 - \mu_{ui}\right) V_o - \mu_{ui} W_o \right) - P(d \mid \hat{\phi}) W_o \quad (2)$$

for a treated, t, and untreated u tree in some assessed health state $\hat{\phi}$. See Table 1 for definitions of all variables and parameters used in all models. The benefit of treatment from the owners perspective is the difference in their payoff between treatment and non-treatment for a tree with a particular assessed state, given by

$$\pi_{t\hat{\phi}} - \pi_{u\hat{\phi}} = \Delta_o k_{\hat{\phi}} \quad (3)$$

where $\Delta_o = V_o + W_o$ is the benefit of avoiding mortality of a focal tree to its owner and

$$k_{\hat{\phi}} = P(h \mid \hat{\phi}) \left(\mu_{uh} - \mu_{th}\right) + P(i \mid \hat{\phi}) \left(\mu_{ui} - \mu_{ti}\right) \quad (4)$$

is the change in the likelihood of tree survival that results from treatment of a tree in assessed state $\hat{\phi}$ (for a more detailed derivation, see Supplementary Material Section B.6). While the value of avoiding tree mortality does not depend on its assessed health state, the likelihood that treatment averts mortality does.

A tree provides benefits not just to its owner but also to the broader community because many of the ecosystem service benefits of urban trees are public goods. Therefore a tree owner's valuation of a surviving tree, V_o, may not align with the municipal value of a surviving tree, V_m, which we assume is also assessed over the time horizon of treatment efficacy. Similarly, W_m is the social cost of tree mortality, which we assume does not include removal costs. From the perspective of the municipality, the benefit of avoiding mortality of a single tree is thus $\Delta_m = V_m + W_m$. While the tree owner considers only direct risks to the survival of their own tree, the municipality also considers the spillover impact of treatment or non-treatment on changes in the likelihood of survival of other trees. This introduces a second source of divergence between the payoffs of the municipality and the private tree owner. These values and costs, together with perceived direct and spillover mortality risks, assessment accuracy, and community level infestation rates can be used to construct the payoff from the perspective of the municipality as

$$\Pi_{t\hat{\phi}} = P(h \mid \hat{\phi}) \left[V_m - \Delta_m \left(\mu_{th} + \lambda_{th}\right)\right] + P(i \mid \hat{\phi}) \left[V_m - \Delta_m \left(\mu_{ti} + \lambda_{ti}\right)\right] - P(d \mid \hat{\phi}) W_m \quad (5)$$

$$\Pi_{u\hat{\phi}} = P(h \mid \hat{\phi}) \left[V_m - \Delta_m \left(\mu_{uh} + \lambda_{uh}\right)\right] + P(i \mid \hat{\phi}) \left[V_m - \Delta_m \left(\mu_{ui} + \lambda_{ui}\right)\right] - P(d \mid \hat{\phi}) W_m \quad (6)$$

for a treated and untreated focal tree that is assessed to be in some health state $\hat{\phi}$ (derivations of these payoff equations are presented in Supplementary Material Section B.7). The benefit of treatment from the socially-oriented perspective of the municipality can be written as

$$\Pi_{t\hat{\phi}} - \Pi_{u\hat{\phi}} = \Delta_m \left(k_{\hat{\phi}} + l_{\hat{\phi}}\right) \quad (7)$$

where

$$l_{\hat{\phi}} = P(h \mid \hat{\phi}) \left(\lambda_{uh} - \lambda_{th}\right) + P(i \mid \hat{\phi}) \left(\lambda_{ui} - \lambda_{ti}\right) \quad (8)$$

is the expected change in community tree survival given treatment of a focal tree in assessed health state $\hat{\phi}$. These equations show that private and municipal benefits of treatment across the scenarios share $k_{\hat{\phi}}$, which describes the effectiveness of treatment for the focal tree given the information that is available. However, whenever $\Delta_m \neq \Delta_o$ or $l_{\hat{\phi}} > 0$, the private and social incentives for treatment will not align.

Cost of treatment. Treatments for forest pests often rely on licensed tree care firms and professionals for their application because of the use of specialized equipment and insecticides. We analyze a model which implicitly considers the role of these firms by implementing a subsidy-dependent treatment cost function that emerges from a model

Table 1
Descriptions and definitions of variables and parameters in the model.

Term	Definition
$\phi \in \{h, i, d\}$	Underlying tree state: healthy, infested, dead/dying
$\hat{\phi} \in \{\hat{h}, \hat{\imath}, \hat{d}\}$	Assessed tree state: healthy, infested, dead/dying
$P(\phi)$	(Prior) probability of a tree being in state ϕ
$P(\hat{\phi} \mid \phi)$	Probability of a tree in some state ϕ being assessed as $\hat{\phi}$ (health assessment accuracy)
$P(\phi \mid \hat{\phi})$	(Posterior) probability of a tree being in state ϕ given that it was assessed as $\hat{\phi}$
τ^*	Planning time horizon
V_o	Value of a surviving tree to its owner over τ^* ('o' subscript indicates the tree owner perspective)
V_m	Value of a surviving tree to society over τ^* ('m' subscript corresponds to a municipal perspective)
W_o	Cost of tree mortality to its owner, including removal costs
W_m	Cost of tree mortality to society
W'_m	Cost of tree mortality to society, including removal costs
Δ_o	Private value of avoiding tree mortality, $V_o + W_o$ (drawn from a uniform distribution, $U(a, b)$)
Δ_m	Social value of avoiding tree mortality, $V_m + W_m$
Δ'_m	Social value of avoiding tree mortality including removal costs, $V_m + W'_m$
$\mu_{t\phi}$	Perceived mortality risk for a treated (subscript 't') tree in health state ϕ
$\mu_{u\phi}$	Perceived mortality risk for an untreated (subscript 'u') tree in health state ϕ
$\lambda_{t\phi}$	Perceived spillover mortality risk for a treated tree in health state ϕ
$\lambda_{u\phi}$	Perceived spillover mortality risk for an untreated tree in health state ϕ
$k_{\hat{\phi}}$	Treatment-based change in a tree's survival probability (tree assessed in state $\hat{\phi}$)
$l_{\hat{\phi}}$	Treatment-based change in survival of other trees (a focal tree assessed in state $\hat{\phi}$)
$\pi_{t\hat{\phi}}$	Payoff to a tree owner of treating a tree assessed as $\hat{\phi}$
$\pi_{u\hat{\phi}}$	Payoff to a tree owner of not treating a tree assessed as $\hat{\phi}$
$\Pi_{t\hat{\phi}}$	Payoff to society of treating a tree assessed as $\hat{\phi}$
$\Pi_{u\hat{\phi}}$	Payoff to society of not treating a tree assessed as $\hat{\phi}$
c	Unsubsidized cost of treatment
$s_{\hat{\phi}}$	Treatment subsidy offered for a tree in assessed health state $\hat{\phi}$
U_o	Utility of tree owner
U_m	Utility of municipality
α	Recovery rate of infested trees that are treated
β	Pest spread rate
γ	Pest-induced mortality rate
ϵ_h	Effectiveness of treatment for a healthy tree
ϵ_i	Effectiveness of treatment for an infested tree

of Bertrand competition among multiple symmetric firms. In Supplementary Material Section C, two key simplifying results about subsidy policies and resulting treatment costs are obtained. First, we show that it is always optimal for the municipality to offer the same subsidy level to all firms. Second, we show that given equal subsidies and symmetric firms, the subsidy will be completely passed on to the tree owner in the form of lower prices. As a consequence of these results, we assume that the price a tree owner pays for treatment is

$$c - s_{\hat{\phi}} \tag{9}$$

where c is the marginal cost of treatment for the firms and $s_{\hat{\phi}}$ is the subsidy level offered by the municipality for treatment of a tree with assessed health state $\hat{\phi}$.

Game structure. Once a tree has had its health status assessed, the municipality chooses subsidy levels, $s_{\hat{\phi}}$, that are available to firms for the treatment of a tree assessed in state $\hat{\phi}$, which results in a treatment cost for the tree owner of $c - s_{\hat{\phi}}$. The tree owner then decides whether to treat their tree or not. While the tree owner knows how much they value avoiding tree mortality, Δ_o, the municipality only know that Δ_o is drawn from a uniform distribution between a and b, denoted $\Delta_o \sim U[a, b]$. A strategy for the tree owner defines their likelihood of choosing treatment across the full range of values from a to b. Formal definitions of the strategy spaces of the players can be found in Supplementary Material Section B.9.

Objective functions. Given the value of treated and untreated trees and the cost of subsidies, we construct the utility function for the municipality. We assume that subsidies, $s_{\hat{\phi}} \geq 0$ are costly to the municipality. This leads to a utility function for the municipality given by

$$U_{m\hat{\phi}} = \begin{cases} \Pi_{t\hat{\phi}} - s_{\hat{\phi}}, & \text{if tree assessed as } \hat{\phi} \text{ is treated} \\ \Pi_{u\hat{\phi}} & \text{if tree assessed as } \hat{\phi} \text{ is untreated} \end{cases} \tag{10}$$

and we assume that the municipality aims to maximize their expected utility when they choose the subsidy levels to offer for each assessed tree health state, $\hat{\phi}$. Finally, we consider the utility of a private tree owner, which will depend on their valuation of the tree. These valuations can be used to construct the utility function of the tree owner as

$$U_{o\hat{\phi}} = \begin{cases} \pi_{t\hat{\phi}} - c + s_{\hat{\phi}}, & \text{if the tree is treated} \\ \pi_{u\hat{\phi}}, & \text{if the tree is untreated} \end{cases} \tag{11}$$

where the owners benefit from their private valuation of a treated or untreated tree, and if the tree is treated, they bear the cost of treatment. We assume that the tree owner makes a treatment decision that maximizes their utility. We use these utility functions to derive the Perfect Bayesian Equilibrium for the game.

Game equilibrium. The analysis of the game is conducted via backward induction, starting with the tree owner's optimal strategy that maximizes their utility given an arbitrary subsidy level. Given this, we compute the optimal subsidy policy of the municipality that maximizes their expected utility, given their beliefs about how the tree owner will respond to the subsidy level offered. In total, this will yield strategies for the municipality and the tree owner that satisfy the conditions of a Perfect Bayesian Equilibrium, assuring that no player will have an incentive to unilaterally deviate from their strategy. Details of the analysis can be found in Supplementary Material Section C.

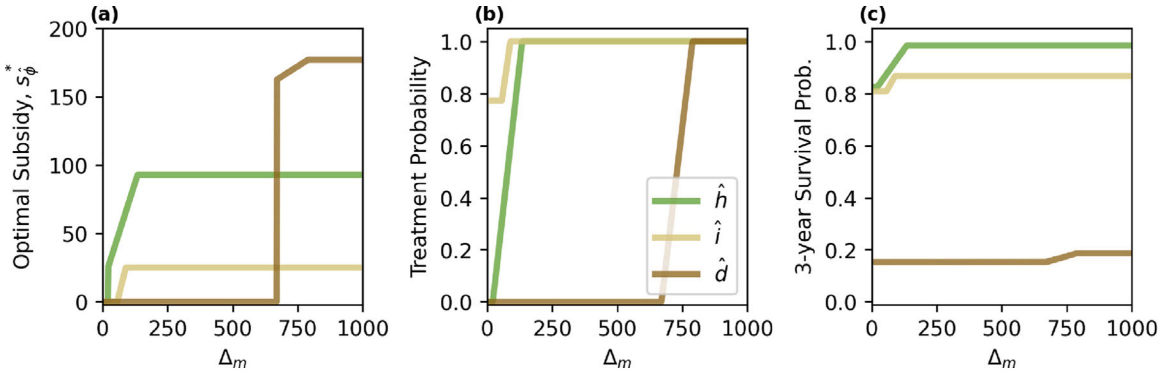

Fig. 2. Optimal subsidy levels, treatment probabilities, and expected 3-year tree survival for privately owned trees. These values vary across assessed tree health states and depend on the social benefit of avoiding tree mortality, Δ_m. These figures show a case where the community infestation state is $(P(h), P(i), P(d)) = (0.8, 0.15, 0.05)$, implying that a pest is widespread but has yet to cause significant tree mortality. Remaining parameters that generated this illustrative example can be found in Table S.M. 1.

We focus on the optimal subsidy policy of the municipality and how this optimal policy impacts treatment rates of a privately owned tree. The equilibrium subsidy policy, defined by the magnitude of subsidy available given different parameter conditions are met, is

$$s^*_{\hat{\phi}} = \begin{cases} 0 & c \le ak_{\hat{\phi}} \\ c - ak_{\hat{\phi}} & c > ak_{\hat{\phi}} \text{ and } c + bk_{\hat{\phi}} - 2ak_{\hat{\phi}} \\ & \le \Delta_m \left(k_{\hat{\phi}} + l_{\hat{\phi}}\right) \\ \frac{1}{2}\left(\Delta_m \left(k_{\hat{\phi}} + l_{\hat{\phi}}\right) + c - bk_{\hat{\phi}}\right) & c > ak_{\hat{\phi}} \text{ and } \mid c - bk_{\hat{\phi}} \mid \\ & < \Delta_m \left(k_{\hat{\phi}} + l_{\hat{\phi}}\right) < c + bk_{\hat{\phi}} - 2ak_{\hat{\phi}} \\ 0 & c > ak_{\hat{\phi}} \text{ and } \Delta_m \left(k_{\hat{\phi}} + l_{\hat{\phi}}\right) \\ & \le \mid c - bk_{\hat{\phi}} \mid \end{cases} \tag{12}$$

where the first case arises when the cost of treatment is low enough that a tree owner will opt for treatment regardless of their type, even in the absence of a subsidy. The second case corresponds to the case where the social value of treatment is high enough to justify a subsidy level that induces even the tree owners with the lowest value for treatment of their tree to choose treatment. The third case corresponds to an intermediate equilibrium where the optimal subsidy level results in a some types of tree owners choosing treatment and others opting not to treat. The final case arises when the social benefit of treatment is too low to justify subsidizing treatment.

When the optimal subsidy levels are positive, they result in increased treatment probabilities for a privately owned tree. The probability that the owner of a focal tree assessed in health state $\hat{\phi}$ will opt for treatment given that equilibrium strategies are followed is

$$P^*_{t\hat{\phi}o} = \begin{cases} 1 & c \le ak_{\hat{\phi}} \text{ or } c + bk_{\hat{\phi}} - 2ak_{\hat{\phi}} \le \Delta_m \left(k_{\hat{\phi}} + l_{\hat{\phi}}\right) \\ \frac{\Delta_m \left(k_{\hat{\phi}} + l_{\hat{\phi}}\right) - c + bk_{\hat{\phi}}}{2k_{\hat{\phi}}(b-a)} & c > a \text{ and } \mid c - bk_{\hat{\phi}} \mid < \Delta_m \left(k_{\hat{\phi}} + l_{\hat{\phi}}\right) < c \\ & + bk_{\hat{\phi}} - 2ak_{\hat{\phi}} \\ \frac{bk_{\hat{\phi}} - c}{k_{\hat{\phi}}(b-a)} & bk_{\hat{\phi}} > c > ak_{\hat{\phi}} \text{ and } \Delta_m \le bk_{\hat{\phi}} - c \\ 0 & c \ge bk_{\hat{\phi}} \text{ and } \Delta_m \left(k_{\hat{\phi}} + l_{\hat{\phi}}\right) \le c - bk_{\hat{\phi}} \end{cases} \tag{13}$$

where the first case arises when treatment costs are low relative to private benefits or when the social value of treatment is high. The second case results under intermediate subsidy levels, and the final two cases result when no subsidies are applied and either some types of tree owners still treat their tree (case 3) or none choose to (case 4). Fig. 2 shows a representative example of optimal subsidies and treatment rates across assessed health classes of trees as a function of the social value of avoiding tree mortality, Δ_m. In this case, trees assessed as infested have a positive treatment probability even in the absence of subsidies. Only for high levels of Δ_m do trees assessed as dying receive subsidies and become treated. Despite treatment probabilities being lower for healthy trees at low values of Δ_m, trees assessed as healthy have higher 3-year survival probabilities than infested trees (based on mortality risk perceptions, $\mu_{t\phi}$ and $\mu_{u\phi}$). This results because mortality requires infestation as a precondition and this delays mortality for healthy trees.

2. Treatment of public trees

Now let us consider an optimization approach applied to municipally owned trees. Much of the setup and notation remains from the prior game theoretic model. We assume that public trees can be treated at a cost, c, by the municipality. The problem for a forest manager is to identify the subset of trees for which the social benefit of treatment is greater than the public cost. While the social value of a surviving tree, V_m, remains unchanged, the social cost of mortality of a municipally owned tree may be higher than the social cost of a private tree's mortality. In the case of a municipally owned tree, we assume this cost is inclusive of the removal cost of the tree. Thus we define W'_m as the social cost of tree mortality, including removal costs. The objective of the municipality for the treatment of public trees is to choose treatment probabilities to maximize

$$U_{m\hat{\phi}} = \begin{cases} \Pi'_{t\hat{\phi}} - c, & \text{if tree assessed as } \hat{\phi} \text{ is treated} \\ \Pi'_{u\hat{\phi}} & \text{if tree assessed as } \hat{\phi} \text{ is untreated} \end{cases} \tag{14}$$

where the expected benefit of treatment is

$$\Pi'_{t\hat{\phi}} - \Pi'_{u\hat{\phi}} = \Delta'_m \left(k_{\hat{\phi}} + l_{\hat{\phi}}\right) \tag{15}$$

and the net social benefit of avoiding tree mortality is $\Delta'_m = V_m + W'_m$. As before, we denote the change in the survival probability in response to treatment for a focal tree assessed in state $\hat{\phi}$ as $k_{\hat{\phi}}$ and the spillover effect of treatment on changes in expected community-level tree survival as $l_{\hat{\phi}}$. This can be used to define the cases where a municipal tree should be treated. The optimal probability of treating a public tree is given by

$$P^*_{t\hat{\phi}m} = \begin{cases} 1 & c \le \Delta'_m \left(k_{\hat{\phi}} + l_{\hat{\phi}}\right) \\ 0 & c > \Delta'_m \left(k_{\hat{\phi}} + l_{\hat{\phi}}\right). \end{cases} \tag{16}$$

This equation provides a strikingly simple proscription for treatment of public trees. However, considerable nuance is encoded within the $k_{\hat{\phi}} + l_{\hat{\phi}}$ because these terms depend on treatment effectiveness, assessment accuracy, the state of EAB infestation within the community and the perceived direct and spillover mortality risks to trees.

3. Forest pest dynamics

The models presented to examine the treatment of a focal public or private tree are based on risk perceptions and treatment choices at a single point in time. This simplifying assumption results in an analytically tractable approach for treatment and subsidy programs, but begs the question of how well such programs might perform over time. We now construct a complimentary model that describes the temporal dynamics of tree infestation and mortality for a population of public and private trees. We build a compartmental epidemiological model (Kermack and McKendrick, 1927) of forest pest spread across a population of public and private trees so that the impact of subsidy policies and treatment decisions on the temporal dynamics of tree infestation and mortality can be evaluated.

We categorize the population of trees into classes with distinct properties that influence the spread of the pathogen, subdividing the population into healthy, infested, and dying classes for municipally owned and privately owned trees. Rates of transfer between compartments describe pest spread, tree mortality, and tree recovery following treatment. We denote municipal trees by the frequency of healthy trees, H_m, infested trees, I_m, and dead or dying trees, D_m (using capital letters to distinguish the population of trees from individual tree states considered earlier). The municipally owned trees interact with three classes of privately owned trees, H_o, I_o, and D_o (o subscripts denote that the ownership of these classes of trees is private, as before). We measure the frequency of trees in each category so that we have $H_m + I_m + D_m + H_o + I_o + D_o = 1$.

We denote the rate of change of the fraction of trees as $\frac{dH_m}{d\tau} = \dot{H}_m$ for healthy municipally owned trees and follow similar notation for the rates of change of other classes of trees. The dynamics of pest spread and tree infestation are governed by

$$\dot{H}_m = -\beta \left(1 - \epsilon_h P_{thm}\right) H_m(I_m + I_o) + \alpha\epsilon_i P_{tim} I_m \tag{17}$$

$$\dot{H}_o = -\beta \left(1 - \epsilon_h P_{tho}\right) H_o(I_m + I_o) + \alpha\epsilon_i P_{tio} I_o \tag{18}$$

$$\dot{I}_m = \beta \left(1 - \epsilon_h P_{thm}\right) H_m(I_m + I_o) - \gamma \left(1 - \epsilon_i P_{tim}\right) I_m - \alpha\epsilon_i P_{tim} I_m \tag{19}$$

$$\dot{I}_o = \beta \left(1 - \epsilon_h P_{tho}\right) H_o(I_m + I_o) - \gamma \left(1 - \epsilon_i P_{tio}\right) I_o - \alpha\epsilon_i P_{tio} I_o \tag{20}$$

$$\dot{D}_m = \gamma \left(1 - \epsilon_i P_{tim}\right) I_m \tag{21}$$

$$\dot{D}_o = \gamma \left(1 - \epsilon_i P_{tio}\right) I_o \tag{22}$$

where P_{tio}, P_{tho}, P_{tim}, and P_{thm} correspond to treatment probabilities of trees that are infested or healthy and privately or municipally owned. These probabilities can be defined to create various treatment scenarios that depend on the state of the system. For instance, treatment probabilities may increase when the community level of infestation $(I_o + I_m)$ is higher. We can also construct treatment scenarios to reflect the results of the game theoretic and optimization models of treatment described by Eqs. (13) and (16). However, these treatment probabilities apply to trees based on their assessed state, whereas the dynamics described in this section depend on treatment probabilities based on a tree's actual health state. These transformations can be calculated with Bayes' theorem, described in Supplementary Material Sections G.1 and G.2.

In contrast to the game theoretic and optimization models, where we relied on mortality risk perception, for example μ_{th}, over a fixed time horizon, this epidemiological model depends only on treatment effectiveness parameters for healthy and infested trees to describe the dynamics of pest spread. The treatment effectiveness parameter for healthy trees, $\epsilon_h \in [0,1]$, describes how effective treatment is at preventing infestation of healthy trees. The treatment effectiveness parameter for infested trees, $\epsilon_i \in [0,1]$, describes the likelihood that treatment will result in tree recovery. The propensity for the pest to spread in the absence of treatment is given by β, which integrates the contact rate of pest to new hosts and the propensity for infestations to become established. The recovery rate for infested trees that are treated effectively is given by α. The mortality rate of infested trees that are untreated or for which treatment is ineffective is γ. A complete derivation of the model structure can be found in Supplementary Material Section F.

4. Emerald ash borer case study

In this section, we integrate the game theoretic and optimization modeling approaches with our dynamical modeling of pest spread to explore the impact of a range of subsidy and treatment scenarios on the dynamics of Emerald ash borer (EAB). EAB is a non-native insect that attacks and kills North American ash (Herms and McCullough, 2014), an important part of urban forests throughout the United States, planted because of their tolerance to drought and soil compaction (MacFarlane and Meyer, 2005). Ash trees provide ecological benefits such as wildlife habitat and stormwater absorption, social benefits such as pleasing environments for people, and human health benefits such as reduced stress and cooling (Dwyer et al., 1992; Pataki et al., 2021). One highly vulnerable ash species, Black ash (*Fraxinus nigra*), is a cultural keystone species for many Native Peoples in North America with spiritual, cultural, and utilitarian significance (Costanza et al., 2017; Siegert et al., 2023). Since EAB was discovered near Detroit, Michigan, and Windsor, Ontario, in 2002, the insect has spread to 36 states in the U.S. and five Canadian provinces (Michigan State University and USDA Forest Service, 2022), killed millions of ash trees (Herms and McCullough, 2014), and cost homeowners and cities hundreds of millions of dollars in losses of property value and damage mitigation (Kovacs et al., 2010; Aukema et al., 2011). In response, cities have developed EAB management plans for public trees, including surveillance of tree health, application of systemic insecticides for tree protection, and preemptive removal of infested or unhealthy trees (Herms and McCullough, 2014). Studies have found that insecticide treatments are effective (McCullough et al., 2011) at preventing infestation. Simulation and optimization studies of urban ash populations show that emphasizing treatment rather than tree removal can result in greater net social benefits (McCullough and Mercader, 2012; Kovacs et al., 2014; Kıbış et al., 2021; Sadof et al., 2023). However, given that investing in treatment for ash trees is a public good, we expect private tree owners to under-invest in treatment in the absence of public policies that support treatment. We apply our models of optimal subsidies and optimal treatment choices to the case of EAB and assess the extent to which these policies sustain ash health at the community scale.

We create three treatment scenarios for privately owned trees where either no treatment occurs, no public subsidies are provided for treatment, or where the optimal subsidy policy is in place for privately owned trees. Leveraging our optimization approach for municipally owned trees, we consider two cases: a non-treatment scenario and an optimal treatment scenario. This creates six scenarios (described in Supplementary Material Section G) that we use to illustrate the impact of treatment and subsidy policies on the dynamics of spread of EAB within a landscape of interacting public and private trees. We examine the relative outcomes of a focus on public land, private land, or both in designing treatment programs and examine the impact of intervention timing on maintaining ash populations. To tailor our case study to the realities of EAB, we draw on the literature for estimates of parameter values, summarized in Table 2 and described in Supplementary Material Section I.

To illustrate how these parameter values translate into treatment scenarios, in Fig. 3 we present the optimal subsidy levels and resulting treatment probabilities for private trees in each assessed tree state and for any state of EAB prevalence (by plotting the subsidy levels on a two dimensional simplex displaying the frequencies of healthy, infested and dying trees). This is compared with the treatment probabilities in the absence of subsidies and the optimal treatment choices for public trees. Each row of panels corresponds to a different assessed tree health

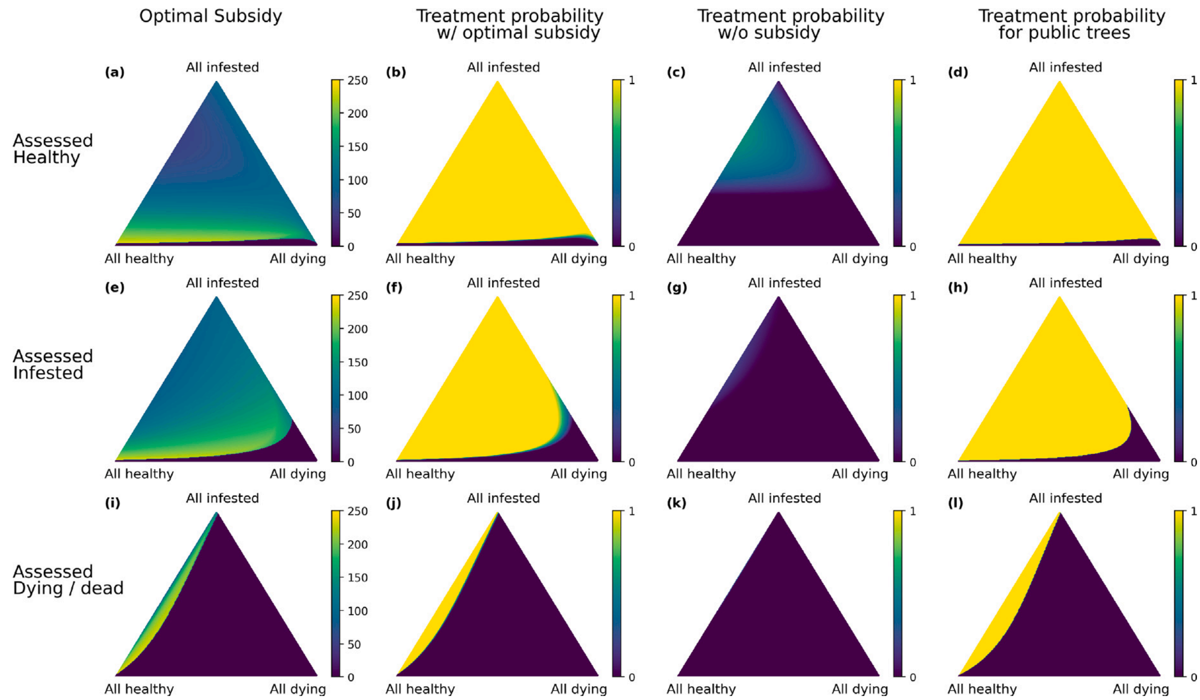

Fig. 3. For a social value of avoiding tree mortality, $\Delta_m = 1150$, we show simplex plots that illustrate equilibrium policies and outcomes across all possible infestation states ($P(h) + P(i) + P(d) = 1$), where the corners of the simplex plots correspond to a state where all trees are in one health class. Each row of panels displays results for a different assessed tree health state. The first column shows how optimal subsidy levels depend on the community infestation state of the pest outbreak. The second column illustrates treatment probabilities for a focal tree with optimal subsidies. The third column illustrates the likelihood of treatment in the absence of subsidies and the last column of plots shows the socially optimal treatment choices for publicly owned trees. For these parameter values, private trees are rarely treated in the absence of subsidies, showing the importance for municipal programs for managing pests on private land.

Table 2
EAB case study parameters.

Parameter	$P(\hat{h} \mid h)$	$P(\hat{i} \mid h)$	$P(\hat{d} \mid h)$	$P(\hat{h} \mid i)$	$P(\hat{i} \mid i)$	$P(\hat{d} \mid i)$	$P(\hat{h} \mid d)$	$P(\hat{i} \mid d)$	$P(\hat{d} \mid d)$
Value	0.89	0.1	0.01	0.49	0.5	0.01	0.01	0.19	0.8
Parameter	Δ_o	Δ_m	Δ'_m	β	γ	α	τ^*	ϵ_h	ϵ_i
Value	$U(675, 1100)$	1150	1850	1	0.3	1	3	0.97	0.5

state. The first column (panels (a), (e), and (i)) shows the optimal subsidy policy for private trees of each assessed health state and the second shows the resulting treatment probabilities, which are used to construct our 'optimal private subsidies' treatment scenario for private trees (panels (b), (f), and (j)). The third column in Fig. 3 (panels (c), (g), and (k)) shows private tree treatment probabilities in the absence of subsidies, highlighting the vast gulf between treatment choices in the presence and absence of optimal subsidies. We use these treatment probabilities to define our 'no private subsidies' treatment scenario for private trees. The final column of Fig. 3 (panels (d), (h), and (l)) shows the optimal treatment choices for public trees, which is used to construct our 'optimal public treatment' scenario for municipally owned trees. For these parameters, optimal subsidy polices nearly align treatment of public and private trees. This need not be the case, however. There exist cases where privately owned trees are more likely to be treated because the municipality can leverage the willingness to pay of private tree owners and get these trees treated at a lower cost than public trees due to cost sharing between the parties, there also exist cases where public trees are treated at higher rates than private trees, even in the presence of optimal subsidies.

We have considered optimal policies for treatment of privately owned trees and seen that these policies could increase the rate of treatment of private trees and can result in more similar management of public and private trees. However, our game theoretic and optimization modeling approaches do not allow for an assessment of the impact of these policies on EAB spread or ash mortality over time. We use the epidemiological model of forest pest dynamics developed to project the dynamics of EAB spread within a community 60% of ash trees that are privately owned and 40% are public. We initialize the simulations to reflect the recent arrival of EAB to a community when nearly all trees are EAB-free (99%) but a few have EAB infestations (1%). In Fig. 4, we show six scenarios of public and private treatment decisions that were constructed based on the outcomes of the game theoretic and optimization models presented in Fig. 3. When subsidies are not implemented and public trees are untreated (panel (b)), ash mortality is indistinguishable from the no treatment scenario (panel (a)) because treatment rates for private trees are low throughout the simulation. The optimal subsidy policy for private trees combined with optimal treatment choices for public trees (panel (f)) still results in EAB spread, almost entirely among privately owned trees. However, 50-year ash survival at the community level is approximately 80%, so the impacts of EAB on aggregate urban forest health in this case will be far more limited than if there was no treatment and over 80% of ash trees died during the first 20 years of infestation.

Population dynamics under these scenarios are represented in a simplex plot in panel (a) of Fig. 5. This helps illustrate the relationship between pest dynamics and treatment policies because as an outbreak unfolds the subsidy levels and treatment outcomes change dynamically. The dynamics in the 'no treatment' case are shown with arrows and black arcs that wends toward the state where nearly all ash trees die. For the scenario where there is 'no public action' (public trees untreated, private trees unsubsidized), there is little treatment by private tree owners, resulting in an indistinguishable trajectory of pest spread. In this plot, we also show the dynamics that would result after the

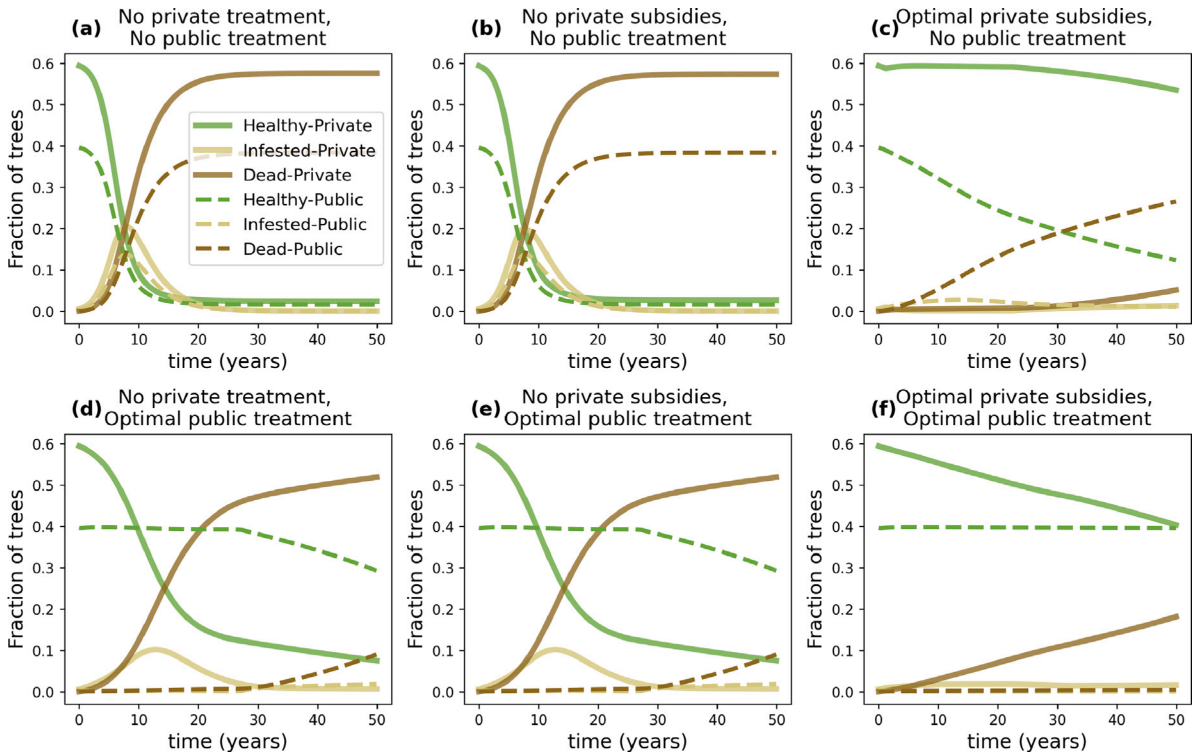

Fig. 4. The predicted 50-year dynamics of EAB spread in an urban forest based on the epidemiological model. In each panel the vertical axis is the fraction of trees in a given health and ownership state. The first row (panels (a), (b), and (c)) shows cases where public trees are untreated whereas the second row (panels (d), (e), and (f)) show cases with optimal treatment of public trees. The first column (panels (a) and (d)) shows simulations where privately owned trees are untreated, the second column (panels (b) and (e)) shows the dynamics of EAB spread when there are no subsidies for the treatment of privately owned trees, and the final column (panels (c) and (f)) shows cases where optimal subsidy levels are set for the treatment of private trees. For these figures, 40% of ash trees are public and 60% are privately owned. Panel (a) corresponds to the 'no treatment' scenario, panel (b) corresponds to the 'no public action' scenario and panel (f) corresponds to the 'optimal policies' scenario. Supplementary Material Figure S.M. 6 shows the joint dynamics averaged across public and private trees.

introduction of 'optimal policies' that guide treatment of public trees and subsidies for privately owned trees. Several cases are shown with different intervention timings. Once the municipality implements an optimal subsidy policy and treatment plan, the EAB infestation levels plummet followed by a period of much slower spread (as shown by the light gray lines heading toward the bottom of the simplex). Panels (b) and (c) in Fig. 5 show that earlier implementation of the optimal policy results in greatly increased long-run healthy ash populations.

In sum, the integration of game theoretic, optimization, and epidemiological modeling applied to the case of EAB shows how treatment polices designed via analytically tractable models can enhance the stewardship of ash trees across private and public lands and slow the spread of EAB at community scales. Given the high prevalence of privately owned trees in urban areas, achieving these outcomes necessitates coordinated action on both public and private land. While the implementation of treatment and subsidy programs is costly, our approach assures that subsidies and treatment are only used when the social benefits (via increased ecosystem service provision and reduced spillover mortality risk) exceed the costs of the programs. We show that early implementation of treatment on public land and support for subsidy programs for private tree owners increases ash survival over a 50-year time horizon, extending the life of ash trees long enough that the community level impact of pest-induced mortality will be less noticeable when paired with replanting. This has the potential to greatly reduce the level of disruption that EAB can otherwise cause in urban communities.

5. Discussion

Urban forests and trees provide a wide range of ecosystem services with benefits that accrue from local to global scales. This can be seen in the relationship between tree cover and home values. Trees on a property increase a home's value, but so does having higher tree cover within the neighborhood (Kovacs et al., 2022). This illustrates that some ecosystem service benefits of trees are local public goods. Carbon sequestration by trees provides an even starker example because the benefit of reduced atmospheric carbon dioxide is a global public good (Buchholz and Sandler, 2021). Therefore, sustaining the ecosystem service benefits of privately owned urban trees resembles an impure public goods problem. This has been central to the challenge of achieving sustainability because public goods result in a conflict between the collective good and individual self-interest (Levin, 2010, 2014). In the case of urban forest management, this implies that private tree owners may under-invest in management interventions that sustain the ecosystem service benefits of their trees. These issues are especially acute in the context of forest pest management because investments in control have spatiotemporal spillover benefits that reduce risks to other nearby trees. In urban forests, these phenomena arise within a mosaic of public and private lands with many uses and distinct management aims. The confluence of these factors creates a unique challenge for urban landscape-scale management of forest pests.

While total eradication of a non-native pest species may not be a realistic target (Green and Grosholz, 2021), slowing the spread of an invasive pest, such as EAB, may still be beneficial (McCullough and Mercader, 2012). For example, if the ash trees in a community are decimated over a 5–15 year period, this significantly disrupts the ecosystem service benefits of trees in areas where ash predominate and imposes major tree removal costs to the public and private tree owners. On the other hand, if these same losses are extended across a 50-year period, then the rate of tree mortality would be closer to the baseline rate within urban areas and the impact of EAB on the provision of ecosystem services would be far less pronounced. This suggests that

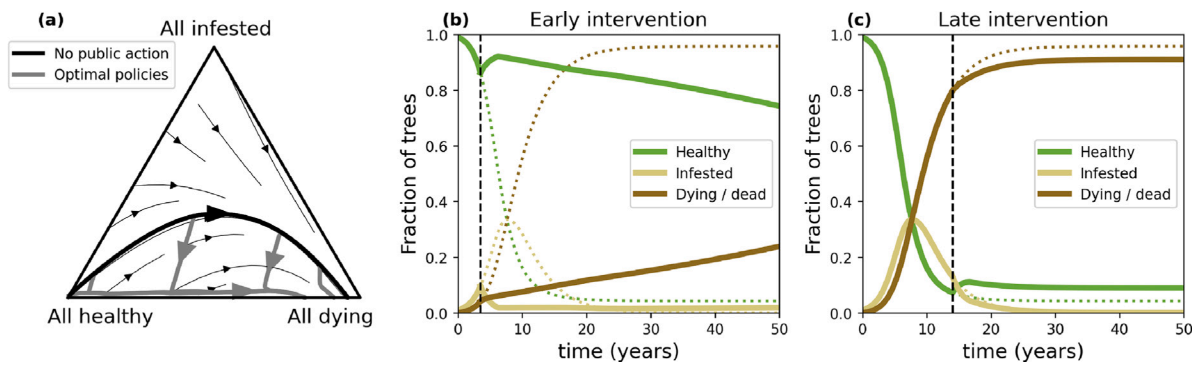

Fig. 5. Intervention timing impacts the success of EAB treatment policies. Panel (a) illustrates the dynamics of EAB under a 'no public action' baseline case where there are no subsidies for the treatment of private trees and no publicly owned trees are treated. These dynamics are shown with black arrows and a representative case is emphasized with a thick line. Under this 'no public action' baseline, private tree owners rarely treat their trees and the infestation spreads largely unimpeded. From this no public action baseline, we simulate the introduction of 'optimal policies' for EAB management. Under our 'optimal policy' scenario, we assume optimal treatment of public trees (described in Supplementary Material Section G.1) and optimal subsidy policies for privately owned trees (described in Supplementary Material Section G.2). The impact of intervention timing is illustrated by simulating the introduction of optimal policies at 3.5 year intervals (shown in gray, with arrows to indicate the direction of dynamics). The impact of intervention timing on 50-year ash tree survival is shown in panels (b) and (c), where outcomes under cases where public policies are enacted 3.5 years and 14 years after EAB arrival, respectively. In these two panels, dotted lines correspond to the counterfactual no public action scenario. The vertical dashed line shows when optimal policies are implemented and the solid lines correspond to the realized dynamics given intervention timing.

both the reduction and delay in mortality seen in our results would be beneficial to communities.

A limitation of our application of the game theoretic and optimization models to community pest dynamics is that we apply an analysis of a representative public or private tree to a whole community by assuming that the outcomes derived from focusing on one tree are representative. This may not be the case if tree care firms or the municipality face increasing marginal costs of treatment (due to a constrained supply of arborists who can administer treatments, for example). While this could be an important feature for managing emergent pests, it is outside the scope of this work. Relatedly, our dynamic model is not spatially explicit and instead assumes that all the trees within the community interact. This assumption would be unrealistic if the model were applied at large spatial scales, but may be reasonable at the scale of a community or municipality. A benefit of this simplicity is that it yields intuition into what determines optimal subsidy policies and testing their impact with the dynamical model is not computationally intensive. As such, these models could form the basis of a tool for considering policies for pest treatment in urban areas.

Recent investments in urban forestry have emphasized environmental justice (USDA Forest Service, 2023b). While our model does not explicitly weigh the distributional effects of treatment subsidies, we can nonetheless consider how the management approach studied in this paper might hinder (or advance) these objectives. The optimal subsidy levels derived in our game theoretic analysis fall into three categories, two of which should not impact inequality. When no subsidy is optimal, then there will be no impact on inequality because no one receives a subsidy. Similarly, when the optimal subsidy is high enough to ensure that all individuals treat their trees we also need not worry about the impact on inequality of the policy because it impacts all ash tree owners the same way. In this case, assuring that the program is being administered equitably could advance environmental justice.

However, there are cases that could generate feedback effects between inequality and the environment (Hamann et al., 2018). When an intermediate subsidy level is optimal, individuals with higher valuations of tree avoiding tree mortality opt for treatment and those with lower valuations decline treatment. Research has found that the relationship between socioeconomic factors and urban forests is complex, context dependent, and shaped by legacy effects (Roman et al., 2018; Grove et al., 2020; Koo et al., 2023). However, positive relationships between income and demand for urban forests have been documented (Zhu and Zhang, 2008; Le Tran et al., 2017). If we assume a positive correlation between socioeconomic indicators and willingness to pay for treatment of ash trees, intermediate subsidy levels could exacerbate inequality because the subsidy will flow to those with higher socioeconomic status. In addition to the direct effect of the subsidy on inequality, there is also the potential for diverging treatment decisions to impact EAB spread and ash decline. For example, in communities with high levels of residential segregation (Massey and Denton, 1988; Logan and Parman, 2017), this could manifest as spatial EAB hotspots that disproportionately impact historically marginalized communities and reinforce inequitable patterns of urban tree canopy cover (Schwarz et al., 2015; Locke et al., 2021). In these cases, it may be worth considering alternative objective functions for the municipality that explicitly weigh distributional effects and equity so that harmful positive feedback effects between inequality and the environment can be avoided.

The management of forest pests in an urban mosaic of public and private land poses unique public goods problems that can be addressed with carefully designed management interventions. We integrate game theoretic, optimization, and dynamical systems approaches, and uncertainty, to study how forests comprised of interacting public and private ownerships can be cost-effectively sustained in the face of threats from pests. Our case study on EAB illustrates how designing public programs to bolster private incentives for investment in public goods could be employed across a range of management challenges and contribute to collective action for sustainability.

CRediT authorship contribution statement

Andrew R. Tilman: Writing – review & editing, Writing – original draft, Visualization, Investigation, Conceptualization. **Robert G. Haight:** Writing – review & editing, Writing – original draft, Investigation, Conceptualization.

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.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.ecolecon.2025.108602.

Data availability

A link to code that generates all figures is available in the acknowledgments section of the manuscript.

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