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Cooperative bargaining to manage invasive species in jurisdictions with public and private lands

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ABSTRACT

Mixed land ownership affects the scope for cooperative bargaining between jurisdictions to undertake control activities to slow the spread of an invasive species. We consider a problem in which emerald ash borer (EAB) spreads from an infested to an uninfested jurisdiction, where both contain ash trees on public and private land. We develop a dynamic model of cooperative Nash bargaining to examine how the mix of land ownership within each municipality affects the path of a negotiated transfer payment from the uninfested to the infested jurisdiction. Using a numerical simulation, we demonstrate that a bargaining agreement can be reached only below a threshold level of public land ownership in the infested municipality. The value of this threshold depends on the effectiveness of the transfer payment in supporting more intensive control efforts, such as tree removal, that delay spread. In a landscape with mixed ownership, free riding by private landowners on the public control effort is one factor that leads to a decrease in this threshold. We also find that in the presence of free riding, a bargaining agreement can only exist if the jurisdictions commit to a path of transfer payments that spans multiple years. This suggests a role for higher government to play in supporting multi-year cross-jurisdictional agreements.

Introduction

Forest bio-invasions cause significant economic losses as pests spread across property boundaries (Holmes et al. 2006; Kocavs et al., 2011; Sydnor et al. 2007). As invasive species spread across the landscape, the control choices made by one decision maker generate an externality by influencing the likelihood that the pest will spread onto other properties. This problem is well studied in the economic literature, typically as a problem in which control decisions are undertaken by neighboring property owners (Atallah et al. 2017; Büyüktahtakin et al. 2013; Epanchin-Niell and Wilen 2012, 2015; Fenichel et al. 2014; Kovacs et al. 2014; Liu and Sims 2016). Control decisions may be made at a range of scales, from private landowners to public entities, such as cities, states, regions, and countries (Wilen 2007).

A complication that is less well studied arises when the landscape contains a mix of publicly and privately owned land that houses the host species. Examples of mixed land ownership include the wildland–urban interface where private property meets undeveloped vegetation (e.g., national forest), and communities with ornamentals on public streets and parks that are interspersed among private property. Mixed land ownership oftentimes means that public land managers are unable to access and treat the host species on private land. In this setting, control decisions on private land can alter the effectiveness of treatment efforts on public land. This affects the incentives of public land managers to undertake costly control activities and, in turn, the spread of the pest over space and time. This is a problem similar to that modeled by Atallah et al. (2017), in which the externalities generated *within* a decision-making unit affect the spread of a pest *across* decision-making units.

In this study, we examine how mixed public-private land ownership within a jurisdiction affects the control incentives of public land managers to slow the spread of an invasive species. Specifically, we are interested in how mixed land ownership affects the incentives of jurisdictions to cooperatively bargain with one another to control the spread of an invasive species from an infested to an uninfested jurisdiction. A number of studies in the economic literature examine cooperative bargaining between actors as a mechanism to slow bio-invasions. Often, cooperative agreements take the form of a transfer payment that facilitates cost-sharing to support higher control efforts in infested areas (Bhat and Huffaker 2007; Kaitala and Pohjola 1988; Sumaila 1997). For example, Bhat and Huffaker (2007) discuss transfer payment schemes to control dispersion of mammal populations over

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time across landowner boundaries. These studies demonstrate that bargaining can play an important role in cooperative control and that transfer payments are important to self-enforcement of pest spread. However, we are not aware of a study that considers whether mixed land ownership might affect the likelihood of actors to engage in bargaining or the form that a bargaining agreement might take.

A current and prototypical example of a cross-boundary invasive species that reproduces in host species across mixed public and private land is the emerald ash borer (*Agrilus planipennis* Fairmaire), hereafter abbreviated EAB. EAB has already destroyed ash trees (*Fraxinus* spp.) throughout the U.S. (Anulewicz et al., 2008). The Twin Cities of Minneapolis and St. Paul, Minnesota have seen the rapid spread of EAB since the pest was initially detected in St. Paul in 2009. EAB quickly spread throughout the region and has now been detected in Olmsted, Winona, Houston, Hennepin, and Dakota counties (Minnesota Department of Agriculture 2014). To control EAB infestation, some municipalities (including St. Paul), have chosen to delay or avoid ash tree removal by using systemic insecticide treatments. Others (including Minneapolis), have chosen to remove ash trees from public lands. Unfortunately, public control of EAB on privately owned land is not possible, and thus it is not surprising that the total estimated costs of controls in the region to all landowners are estimated to range in the billions (Kovacs et al. 2010, 2011).

In our analysis, we propose a dynamic bio-economic model to study the potential for cooperative bargaining across municipalities to control EAB spread. Our approach is novel in that we allow for a mix of public and private land within municipalities, while also allowing a mechanism for cooperative bargaining across municipalities.[1] Cooperative bargaining involves a transfer payment from an uninfested to an infested municipality to encourage greater levels of control than the infested municipality would choose in isolation. By adopting higher-intensity control, the infested municipality's costs of control increase, but the probability that the pest will spread to the uninfested municipality decreases. Thus, both municipalities stand to gain from bargaining with one another to reach a cooperative agreement. We model the agreement outcome using an axiomatic Nash bargaining approach to demonstrate how the nature of a bargaining outcome depends on land ownership within each municipality.

The Nash method we choose for bargaining is less important here than the basic (and real) problem of differences in incentives to control across adjacent municipalities. Spread of EAB in our model occurs over time according to a biological equation of motion, and we consider the realistic possibility that private landowners may free ride on public control efforts supported by a bargaining agreement. We calibrate our model with data on the EAB infestation from the Twin Cities, where a mix of private and public land ownership affects the benefit and costs of public control efforts. We use this case to demonstrate the utility of our model, but the basic approach we propose is transferable to any situation where municipalities have the opportunity to cooperate to control the spread of an invasive species, but where local governments have limited or no access to private lands to implement control activities.

In our model, mixed land ownership influences the bargaining agreement via two effects. An increase in public lands means that higher-intensity control is undertaken on more land (a direct effect), but at the same time a dollar of transfer payments is spread over a larger land base (an indirect effect). The latter effect reduces the marginal efficacy of the transfer payment in slowing EAB spread. We find that these competing forces drive the bargaining solution away from the first-best outcome as public land ownership increases. However, we also find that the effect of public land ownership on the agreement is non-linear: there is a threshold in the proportion of public lands in the infested municipality above which bargaining is not feasible. Below the threshold, bargaining reduces social costs substantially, relative to the disagreement outcome. Above the threshold, the jurisdictions revert to the disagreement outcome and maximum social costs. We show that the value of this threshold is a function of any activity that reduces the efficacy of the transfer in slowing spread, including free riding by private landowners on the public control effort. As free riding increases, the threshold decreases, which reduces the viability of cooperative bargaining as a mechanism to control the invasion. Thus, land ownership is a critical concern in choosing how to manage forest invasive species in jurisdictions with mixed land ownership.

The remainder of this paper is organized as follows. Section 2 describes the modeling framework for a bilateral Nash cooperative bargaining problem between an uninfested and an infested municipality, where each contains a mix of public and private land ownership. Section 3 describes the data we use to numerically simulate the cooperative bargaining outcome. Section 4 presents results and sensitivity analyses for a range of values in the proportion of public land ownership as well as free riding by private landowners in the infested municipality. Section 5 presents conclusions.

Theoretical model of pest control

Suppose at time $t = 0$ there is a municipality infested by EAB, denoted by subscript I. The municipality is adjacent to an uninfested municipality denoted by subscript U. Let the constants $(0 \leq q_I \leq 1)$ and $(0 \leq q_U \leq 1)$ define the proportion of public land in each municipality (where $1{-}q_I$ and $1{-}q_U$ are the proportions of private land). In the absence of cooperation, the uninfested municipality faces a probability at time t, $0 \leq p(t) \leq 1$, that EAB will spread from the infested municipality.[2] Biological pest spread grows according to $\dot{p}(t) = f(p(t))$, where $\dot{p}(t) = dp(t)/dt$ is the rate of growth in the probability of spread and $f(p(t))$ is a biological growth function for which $f'(p(t)) > 0$.

Our focus in this analysis is on the problem facing these municipalities prior to spread of EAB from the infested to the uninfested location. In this context, the infested municipality will under-control EAB relative to the socially optimal level because it does not benefit from the external net benefits of control to the uninfested municipality. It is therefore reasonable to expect that the uninfested municipality has an incentive to provide assistance to the infested municipality. We consider this assistance in the form of a transfer payment, $\tau(t) \geq 0$, which is made from the uninfested municipality to the infested municipality at time t in return for higher-intensity control in the infested location. We model the control in the infested municipality as an index that increases in intensity with the size of the transfer payment. An increase in control intensity in the context of EAB usually involves the removal of ash trees, though the control index is sufficiently general that it may capture a change in the mix of control activities, such as increased monitoring or more aggressive treatments with insecticide.[3]

The transfer payment from the uninfested municipality is used to support the control of EAB on public lands in the infested municipality.

[1] Our work also differs from Berry et al. (2017), who consider switching frontiers explaining control of EAB where it may or may not be optimal to invest in these activities. Our focus is on cooperative bargaining and the importance of private and public land mix, for ranges of invasion possibilities that are relevant for cooperative mechanisms.

[2] In some cases, it may not be possible to reduce the probability of spread to zero, for example if a small population of the invasive species remains despite treatment efforts. We assume a lower bound of zero without a loss; the model is sufficiently flexible to incorporate an arbitrary, exogenous lower limit such that $p_{min} \leq p(t) \leq 1$.

[3] In this analysis, the mechanism available to the uninfested municipality to prevent infestation is to slow the spread of EAB from the infested municipality. We do not model the choice of *ex ante* control in the uninfested location, such as the preemptive removal of ash trees. However, we do take into account the fact that once the uninfested municipality becomes infested, it must then use costly control within its own boundaries, both to preserve the ash canopy and also to remove dead and dying ash trees that pose a public safety hazard.

These are the lands to which public land managers have direct and immediate access.[4] The efficacy of the transfer payment in stemming the spread of EAB is therefore related to the size of the payment as well as the mix of public and private land in the infested municipality. The transfer payment modifies the biological probability of spread in the following way:

$$\dot{p}(t) = f(p(t)) - q_I b(q_I)\tau(t) \tag{1}$$

This specification captures two effects of the proportion of public land, q_I, on the rate of spread. This proportion does not affect the biological growth function (the first RHS of Eq. (1)), but it does affect the efficacy of the transfer payment albeit in a possibly non-monotonic way. As we show below, the proportion of public land affects the expected costs and benefits of controlling spread through the second RHS term in Eq. (1). This term shows that the proportion of public land has both direct and indirect effects on the spread probability. The multiplicative q_I term on the RHS of Eq. (1) captures a direct effect: as q_I increases, more public land is subject to control, which decreases growth in the probability of spread. The term $b(q_I)$ on the RHS of Eq. (1) captures a second, indirect effect: as q_I increases, a dollar of transfer payment is spread over a larger public land base. This has the effect of diluting the marginal efficacy of a dollar of transfer payment, such that $b'(q_I) < 0$. Also, as we discuss and investigate in more detail later in the simulation section 3, and the incentives to bargain in Eq. (5) below, a shift downward in $b(q_I)$ represents free riding by private landowners to controls on public lands, thereby decreasing the efficacy of any transfer payment. We refer to this indirect effect as the "intensive margin effect" of public land. The direct and intensive margin effects act counter to one another, where $\partial\dot{p}(t)/\partial q_I = -\tau(t)[b(q_I) + q_I b'(q_I)]$. The term in square brackets on the right-hand side is ambiguous in sign. When the direct effect exceeds the indirect effect, i.e., $b(q_I) > q_I b'(q_I)$, an increase in the proportion of public land decreases the rate of spread. Conversely, when $b(q_I) < q_I b'(q_I)$, an increase in the proportion of public land increases the rate of spread.

Absent a higher level of government that requires or funds it, any transfer payment would necessarily result from negotiation between the public decision makers representing each municipality.[5] This is conveniently captured using a bargaining mechanism, where municipalities seek an agreement over both a transfer paid by the uninfested municipality and a control strategy undertaken by the infested municipality. If an agreement is reached, it reduces the probability of spread to the uninfested municipality through Eq. (1). The proportion of public land, q_I, is important to the result of any agreement, because private landowners have little or no incentive to include benefits outside of their land in their own control decisions. We assume that each municipality knows and takes as given the control decisions of private landowners prior to bargaining.[6] For now, we also assume that private landowners' control decisions are not affected by public control or by any agreement between municipalities.[7] We consider the potential for free riding by private landowners on the public control effort by altering the function $b(q_I)$ in the simulation analysis, where a shift down in $b(q_I)$ represents an increase in free riding.

The payment of a transfer and the corresponding increase in control in the infested municipality are reflected in the definition of the net benefits to each municipality. It is instructive now to define these net benefits under the different possibilities for negotiation and spread. The cornerstone of our model is the reality that government treatments are applied only to public land should an agreement over the transfer payment and controls be made. We define the net benefits of ash trees on public land in the infested municipality as $V_{I,public}(\tau(t))$. Because the transfer payment supports the removal of ash trees (higher-intensity control), the net benefit function for public land is decreasing and concave in the transfer payment, i.e., $V'_{I,public}(\bullet) < 0$ and $V''_{I,public}(\bullet) \le 0$. The net benefit function for ash trees on private land is $V_{I,private}$, which does not depend on $\tau(t)$ because transfer payments involve greater control on only public land.

Should an agreement over the transfer payment and control be reached, i.e., $\tau(t) > 0$, the potential net benefits for the infested municipality are a function of the probability of spread, the proportion of public land, and the transfer payment:

$$\Pi_I(q_I, \tau(t)) + \tau(t) = q_I V_{I,public}(\tau(t)) + (1-q_I)V_{I,private} + \tau(t) \tag{2}$$

If an agreement is not reached, then $\tau(t) = 0$ and the infested municipality has net benefit in (2) written as $\Pi_I(q_I, 0)$.

The net benefits to the uninfested municipality depend on additional possibilities, given that the uninfested municipality may stay uninfested through time or at some point it may become infested as EAB spreads. Let $\overline{V}_{U,public}$ and $\overline{V}_{U,private}$ denote the maximum level of net benefits on public and private land if the municipality remains uninfested, i.e., when there has not been spread with probability $1-p(t)$. Let $V_{U,public}$ and $V_{U,private}$ denote the level of net benefits on public and private land if the municipality becomes infested, where $V_{U,public} < \overline{V}_{U,public}$ and $V_{U,private} < \overline{V}_{U,private}$. These terms include the costs of control that would be undertaken on public and private land once EAB spreads into the municipality.[8]

There are four outcomes possible under bargaining for the uninfested municipality: two outcomes are possible if bargaining succeeds and two are possible if a bargaining agreement fails. If a bargaining agreement is reached, the uninfested municipality may remain uninfested or it may become infested at any point in time despite reaching an agreement (e.g., Eq. (1) indicates that a transfer does not guarantee absence of spread). Should an agreement over the transfer payment and control be reached, i.e., $\tau(t) > 0$, and the uninfested municipality remains uninfested, its net benefits are defined as:

$$\overline{\Pi}_U(q_U) - \tau(t) = q_U \overline{V}_{U,public} + (1-q_U)\overline{V}_{U,private} - \tau(t) \tag{3a}$$

given that the municipality has paid the transfer payment. Should infestation occur even with an agreement, this municipality has net benefits that reflect the scale of the damage and are that are therefore less than or equal to the maximum achievable in (3a). If an agreement over the transfer payment and control is reached and the uninfested municipality becomes infested, its net benefits are defined as:

[4] In some cases, public land managers can influence actions on private lands. For example, a dead or dying tree on private property constitutes a safety hazard and is actionable by a municipality. However, it is unlikely that a municipality would undertake the same level of preventive control on private land as on public land, if for no other reason than budgetary limitations. For simplicity, we restrict our attention in this analysis to public control on public land, though public control on private land is an extension that may be considered in a future analysis.

[5] In the case of the Twin Cities, the local government in each municipality would be involved in bargaining. However, in the model the agents involved in bargaining could easily be state governments or even countries in a more general sense.

[6] In this model, we assume that the two municipalities are the same except for their initial states of infestation. We also assume that the level of control and transfer payment are closely related and we can therefore specify the net benefit function to the public landowner as a function of the transfer payment only. The net benefit functions for private landowners are the same with and without bargaining, given our assumption concerning the lack of private control in response to cooperation between municipalities on public land.

[7] Control activities by private landowners under bargaining are assumed to be the same as to those under no bargaining. If anything, there would be free riding by the private landowners under an agreed-upon transfer payment. Thus, the probability of spread would increase through a smaller value for $b(q_I)$ on the right-hand side of Eq. (1). In the numerical simulation, we will examine the effect of free riding by private landowners on the bargaining outcome. It is possible that in some cases, public entities may be able to exert control on private lands, though we consider only public control on public land in this analysis.

[8] The net benefits to the uninfested municipality do not depend directly on the transfer payment. Rather, the transfer payment affects expected net benefits in the uninfested municipality by affecting the probability of spread.

$$\Pi_U(q_U) - \tau(t) = q_U V_{U,public} + (1-q_U)V_{U,private} - \tau(t) \quad (3b)$$

If there is no agreement, $\tau(t) = 0$, and the uninfested municipality remains uninfested, it earns net benefit in (3a) written as $\overline{\Pi}_U(q_U)$. If there is no agreement and the municipality becomes infested, it earns net benefit in (3b) written as $\Pi_U(q_U)$.

By weighting the net benefits for the uninfested municipality in (3a) and (3b) by the probability of spread, we define the expected net benefits for the municipality. If a bargaining agreement is reached, the expected net benefits for the uninfested municipality are given by:

$$E_U(q_U, \tau(t)) - \tau(t) = p(t)\Pi_U(q_U) + (1-p(t))\overline{\Pi}_U(q_U) - \tau(t) \quad (4a)$$

If no agreement is reached, the probability of spread differs for the uninfested municipality. Let $p(t)|_{\tau=0}$ denote the probability of spread in the absence of an agreement, where $p(t)|_{\tau=0} > p(t)$. In this case, the expected net benefits for the uninfested municipality are given by:

$$E_U(q_U, 0) = p(t)|_{\tau=0}\Pi_U(q_U) + (1-p(t)|_{\tau=0})\overline{\Pi}_U(q_U) \quad (4b)$$

Incentives to bargain

The incentives to bargain at any given time period for each municipality indicate the potential scope for agreement. For the infested municipality, the additional benefits from higher controls must exceed the higher costs less the transfer payment. There is an incentive for the infested municipality to bargain in any given time period if $\Pi_I(q_I, \tau(t)) + \tau(t) \geq \Pi_I(q_I, 0)$. For the uninfested municipality, the transfer payment must not exceed the gain in net benefits due to a decreased risk of spread from the infested municipality. There is an incentive for the uninfested municipality to bargain in any given time period if $E_U(q_U, \tau(t)) \geq E_U(q_U, 0)$. By combining these conditions with Eqs. (2), (4a), and (4b), we obtain the static contract region for bargaining agreement in any given time period:

$$q_I[V_{I,public}(0) - V_{I,public}(\tau(t))] \leq \tau(t) \leq (p(t)|_{\tau=0} - p(t))[\overline{\Pi}_U(q_U) - \Pi_U(q_U)] \quad (5)$$

A positive transfer payment will be agreed upon in a single period if it lies in the contract possibilities region specified by (5). The lower bound on the transfer payment in Eq. (5) depends on the loss to the infested municipality from bargaining, which occurs as the infested municipality loses ash trees that are removed as it undertakes higher-intensity control on its public lands. The lower bound increases in q_I: as the proportion of public land in the infested municipality increases, the contract region shrinks.[9]

The upper bound on the transfer payment in Eq. (5) is the change in net benefits if the uninfested municipality becomes infested, weighted by the change in the probability of spread when an agreement is reached. If a bargaining agreement does little to reduce the probability of spread, the upper bound decreases and the contract region shrinks. In contrast, if an agreement substantially reduces the probability of spread, the uninfested municipality faces a greater incentive to bargain. Notice also the explicit importance in the differences in probabilities term (RHS of Eq. (5)) by free riding of private landowners on the public control effort as captured by the function $b(q_I)$ in Eq. (1). A shift down in $b(q_I)$ represents an increase in free riding and leads to an absolute decrease of this probability difference through lower efficacy of a positive transfer payment and a subsequent decrease in incentives to bargain.

Full cooperation (first-best) outcome

The theoretical first-best outcome is one of full cooperation between the two municipalities. The solution to the full cooperation problem is conceptualized as one in which a social planner chooses a path of transfer payments over time to maximize the sum of the present value of net benefits of both municipalities. This solution corrects the externality inherent in the infested municipality's individual control decision. The social planner's objective is to choose a transfer payment according to the following problem:

$$\max_{\tau(t)} \int_0^T e^{-\rho t}\{\Pi_I(q_I, \tau(t)) + E_U(q_U, \tau(t))\}dt \quad (6)$$

subject to Eq. (1) and initial condition $p(0) = p_0$. The Hamiltonian for this problem is $H(\tau(t), p(t), \lambda(t), q_I, q_U) = \Pi_I(q_I, \tau(t)) + E_U(q_U, \tau(t)) + \lambda(t)[f(p(t)) - q_I b(q_I)\tau(t)]$.

Letting $\tau^c(t)$ denote the transfer payment in the full cooperation outcome, the necessary and sufficient conditions for problem (6) are:

$$\frac{\partial H(\bullet)}{\partial \tau(t)} = q_I V'_{I,public}(\tau^c(t)) - \lambda(t)q_I b(q_I) = 0 \quad (7)$$

$$\frac{\partial H(\bullet)}{\partial p(t)} = \overline{\Pi}_U(q_U) - \Pi_U(q_U) - \lambda(t)f'(p(t)) = \dot{\lambda}(t) - \rho\lambda(t) \quad (8)$$

$$\lambda(T) = 0 \quad (9)$$

Combining Eqs. (7) and (8) yields the time path for the first-best transfer payment:

$$\dot{\tau}^c(t) = \frac{b(q_I)[\overline{\Pi}_U(q_U) - \Pi_U(q_U)]}{V''_{I,public}(\tau^c(t))} + \frac{(\rho - f'(p(t)))V'_{I,public}(\tau^c(t))}{V''_{I,public}(\tau^c(t))} \quad (10)$$

The rate at which the first-best transfer payment, $\tau^c(t)$, changes over time depends on the relative magnitudes of the first and second term on the right-hand side of Eq. (10). The first term on the right-hand side of (10) is negative, which implies that the path of transfer payments decreases over time. The second term is ambiguous in sign and depends on the difference between the discount rate and the growth rate for the probability of spread, $\rho - f'(p(t))$. If $\rho - f'(p(t)) < 0$, the second term on the right-hand side of (10) is negative. If the growth rate of spread exceeds the interest rate, there is an incentive to increase transfer payments and condense them into a shorter time frame in order to quickly reduce the probability of spread.

The first-best path of transfer payments also depends on the loss in net benefits if the uninfested municipality becomes infested, given by $\overline{\Pi}_U(q_U) - \Pi_U(q_U)$. The potential loss in net benefits is positive by definition. An increase in this difference implies that the uninfested municipality has more to gain from slowing spread and forestalling a loss in net benefits. This creates an incentive to quickly reduce the probability of spread with large transfer payments in early periods of the problem.

A change in the proportion of public land in the infested municipality, q_I, affects the transfer payment path via its effect on the intensive margin, as captured by $b(q_I)$. Recalling that $b'(q_I) < 0$, an increase in q_I decreases the rate at which the path of transfer payments changes over time. When there are more publicly owned lands in the infested municipality, the transfer payment is spread over a larger land base, which decreases the efficacy of control. This increases the probability that EAB will spread to the uninfested municipality. Thus, the optimal control of EAB is consistent with a path of transfer payments that is more spread out over a longer period of time.

[9] It is possible that invasion is such that either the pest would never spread or bargaining would not slow the spread. In these cases, the incentives to bargain would approach zero because the first RHS term in Eq. (5) would approach zero. We capture this possibility by assuming either q_I or $b(q_I)$equal zero. From Eq. (1), this would mean that the transfer payment cannot affect the probability of spread in any time period. In a simulation analysis, we allow for these cases and conduct sensitivity analyses for these parameters. In addition, if $b(q_I)$ approaches one, then as one reviewer pointed out the problem may become supermodular (i.e., control actions are strategic complements) in the sense that we would implicitly assume that private landowners have an incentive to undertake higher controls given that the government undertakes higher controls in the infested municipality. This would represent a decrease to zero in free riding of private landowners off of public land controls and thereby increase the incentives to bargain through (5), as the RHS term would become more positive.

Nash bargaining outcome

Suppose now that we allow the two municipalities to bargain over a transfer payment. A convenient way to model this problem is to use an axiomatic Nash bargaining approach. Using this approach, the outcome of the bargaining process is defined as that which maximizes the product of the net gains from bargaining in the two municipalities. The net gains from bargaining are defined as the net benefits earned for each municipality with a positive transfer payment less the net benefits in the uncoordinated (disagreement) outcome with no transfer payment. This problem is given by:[10]

$$\max_{\tau(t)} \int_0^T e^{-\rho t}\{[\Pi_I(q_I, \tau(t)) + \tau(t) - \Pi_I(q_I, 0)]^{\gamma_I}[E_U(q_U, \tau(t)) - \tau(t) - E_U(q_U, 0)]^{\gamma_U}\}dt \tag{11}$$

subject to Eq. (1) and initial condition $p(0) = p_0$. In problem (11), ρ is the discount rate and the weights $0 \le \gamma_I \le 1$ and $0 \le \gamma_U \le 1$ represent the relative bargaining power of the infested and uninfested municipalities, respectively, where $\gamma_I + \gamma_U = 1$. All other terms in (11) are defined in Eqs. (2), (4a), and (4b).

Following Ehtamo et al. (1988), the Hamiltonian for problem (11) can be written as: $\widetilde{H}(\tau(t), p(t), \lambda(t), q_I, q_U, \mu_I, \mu_U) = \mu_I[\Pi_I(q_I, \tau(t)) + \tau(t) - \Pi_I(q_I, 0)] + \mu_U[E_U(q_U, \tau(t)) - \tau(t) - E_U(q_U, 0)]$.

$+ \lambda(t)[f(p(t)) - q_I b(q_I)\tau(t)]$

Letting $\tau^b(t)$ denote the path of transfer payments that solves (11), the weights μ_I and μ_U are defined as:

$$\mu_I = \gamma_I[\Pi_I(q_I, \tau^b(t)) + \tau^b(t) - \Pi_I(q_I, 0)]^{\gamma_I - 1}[E_U(q_U, \tau^b(t)) - \tau^b(t) - E_U(q_U, 0)]^{\gamma_U} \tag{12a}$$

$$\mu_U = \gamma_U[\Pi_I(q_I, \tau^b(t)) + \tau^b(t) - \Pi_I(q_I, 0)]^{\gamma_I}[E_U(q_U, \tau^b(t)) - \tau^b(t) - E_U(q_U, 0)]^{\gamma_U - 1} \tag{12b}$$

In the transformed Hamiltonian, $\widetilde{H}(\bullet)$, the weights in (12a) and (12b) for the infested and uninfested municipality, respectively, are functions of the relative net gains from bargaining and the relative bargaining power coefficients for both municipalities.

Given (12a) and (12b), the necessary and sufficient conditions for problem (11) are given by terminal condition (9) along with:[11]

$$\frac{\partial \widetilde{H}(\bullet)}{\partial \tau(t)} = \mu_I q_I V'_{I,public}(\tau^b(t)) + \mu_I - \mu_U - \lambda(t) q_I b(q_I) = 0 \tag{13}$$

$$\frac{\partial \widetilde{H}(\bullet)}{\partial p(t)} = \mu_U[\overline{\Pi}_U(q_U) - \Pi_U(q_U)] - \lambda(t) f'(p(t)) = \dot{\lambda}(t) - \rho\lambda(t) \tag{14}$$

Combining Eqs. (13) and (14) yields the time path for transfer payments in a bargaining agreement:

$$\dot{\tau}^b(t) = \frac{\mu_U}{\mu_I}\frac{b(q_I)[\overline{\Pi}_U(q_U) - \Pi_U(q_U)]}{V''_{I,public}(\tau^b(t))} + \frac{(\rho - f'(p(t)))V'_{I,public}(\tau^b(t))}{V''_{I,public}(\tau^b(t))} + \frac{\rho - f'(p(t))}{q_I V''_{I,public}(\tau^b(t))}\left[\frac{\mu_I - \mu_U}{\mu_I}\right] \tag{15}$$

In contrast to the first-best transfer path in Eq. (10), now the transfer payment path also depends on q_I directly, which enters the final term on the right-hand side of Eq. (15).

The way in which the path depends on q_I is a function of the difference in the weights from expressions (12a) and (12b). To examine how q_I affects the transfer payment path, we differentiate (15) with respect to q_I to derive the comparative statics result:

$$\frac{\partial \dot{\tau}^b(t)}{\partial q_I} = \frac{\mu_U}{\mu_I}\frac{b'(q_I)[\overline{\Pi}_U(q_U) - \Pi_U(q_U)]}{V''_{I,public}(\tau^b(t))} - \frac{\rho - f'(p(t))}{q_I^2 V''_{I,public}(\tau^b(t))}\left[\frac{\mu_I - \mu_U}{\mu_I}\right] \tag{16}$$

Eq. (16) illustrates the importance of the mix of land ownership to any bargaining agreement. The first term on the right-hand side is positive, which implies that an increase in public lands in the infested municipality slows the rate of change in the transfer payment path, resulting in payments over a longer time horizon. Whether the second term on the right-hand side of (16) enhances or counteracts this effect depends on the signs of $\rho - f'(p(t))$ and $\mu_I - \mu_U$. Suppose that $\rho - f'(p(t)) < 0$ so that growth in the probability of spread outpaces the interest rate. In this case, if $\mu_I > \mu_U$, the second term is negative, which pushes the path toward a steeper, quicker reduction in the probability of spread. If $\mu_I < \mu_U$, more public land pushes the path toward a solution that involves a longer path of transfer payments. The relative magnitudes of the weights in (12a) and (12b) is complex and depends on the relative bargaining power of the municipalities as well as their net gains from reaching a bargaining agreement. In the numerical simulation, we explore in greater depth how these weights, the proportion of public land, and the intensive margin effect, influence the path of transfer payments that emerges from a bargaining agreement.

Comparison of first-best and bargaining outcomes

To compare the first-best and bargaining paths, we consider the difference between Eqs. (10) and (15):

$$\dot{\tau}^c(t) - \dot{\tau}^b(t) = \left[\frac{\mu_I - \mu_U}{\mu_I}\right]\left\{\frac{b(q_I)[\overline{\Pi}_U(q_U) - \Pi_U(q_U)]}{V''_{I,public}(\tau^b(t))} - \frac{\rho - f'(p(t))}{q_I V''_{I,public}(\tau^b(t))}\right\} \tag{17}$$

Eq. (17) demonstrates that the proportion of public lands, q_I, drives a difference between the first-best and bargaining paths directly (via the last term on the right-hand side) and indirectly, via $b(q_I)$. Only in the case in which $\mu_I = \mu_U$ are the transfer payment paths identical across the two solutions. When $\mu_I \ne \mu_U$, the bargaining path diverges from the first-best solution. In this case, the bargaining path may involve larger payments early to quickly reduce the probability of spread, or it may involve smaller payments over a longer period of time. The direction of the change, as well as the magnitude of the difference between paths, is an empirical question. We turn to this question with a numerical simulation representative of the case of EAB spread.

Application to emerald ash borer

We explore our theoretical results in greater detail by developing a numerical simulation that characterizes the path of transfer payments and probability of spread in the uncoordinated, first-best, and bargaining problems. We apply our model to the control of EAB spread

[10] Another cooperative bargaining solution was proposed by Kalai and Smorodinsky (1975), which does not require independence of irrelevant alternatives, like Nash does, but instead requires monotonicity of player utilities in the solution. Independence of irrelevant alternatives generally holds in our problem. For example, an optimal bargaining outcome with a positive transfer payment always makes both municipalities better off relative to other transfer payments which are not relevant in that they would not be chosen voluntarily. Examples of irrelevant transfers are those that reduce net benefits to either municipality relative to the disagreement outcome, such as a transfer that is too low to compensate the infested municipality for losses in nonmarket goods by higher controls, or that does not affect the probability of spread enough to compensate the uninfested municipality for the payment made to the infested municipality. These irrelevant alternative outcomes would not be voluntarily chosen and would therefore not affect the transfer that satisfies incentives to bargain in Eq. (5) and that solves the problem in expression (11). A similar argument could be made for any larger set of (inferior) agreements, such as delaying the start of the initial transfer from the uninfested to the infested municipality.

[11] Ehtamo et al. (1988) prove that the necessary conditions that emerge from the Hamiltonian that treats the weights in (12a) and (12b) as constants produces the Nash bargaining solution. In the simulation analysis of section 3, we follow Ehtamo et al. iterating across these weights and the transfer payment path until converging to the optimal solution.

across the Twin Cities of Minneapolis and St. Paul, Minnesota.[12] Using the simulation, we develop insight into the nature of the bargaining outcome when EAB spreads across municipalities that include public and private lands. In sensitivity analyses, we explore how the proportion of land under public control, q_I, and the degree of free riding on private land, captured by a shift in $b(q_I)$, affect the bargaining outcome.

Parameterization and calibration

We calibrate the simulation model using parameter values and functional forms that replicate features of the spread and control of EAB in the Twin Cities and that are published in the literature, to the extent possible. From the theoretical model, we define functional forms for the non-market net benefits of tree cover on public land in the infested municipality, $V_{I,public}(\tau(t))$; the probability of spread growth function, $f(p(t))$; and the intensive margin effect, $b(q_I)$. The functional forms are given by:

$$V_{I,public}(\tau(t)) = V_{I,public}(0) + c\tau(t) + d\tau(t)^2 \tag{18}$$

$$f(p(t)) = rp(t) \tag{19}$$

$$b(q_I) = -a\ln(q_I) \tag{20}$$

In Eqs. (18)–(20), we require that c, $d < 0$, $r > 0$, and $a > 0$. Our choices of functional forms ensure that the assumptions in the theoretical model hold: $V_{I,public}(\bullet)$ is decreasing and concave in $\tau(t)$; $f(\bullet)$ is increasing in $p(t)$; and $b(\bullet)$ is decreasing and concave in q_I.

The baseline parameter values used in the simulation are presented in Table 1. The values for these parameters are based on data collected as part of pest monitoring and control in the Twin Cities. As a starting point, we assume that the two municipalities are identical except for their initial state (infested versus uninfested). Specifically, we assume that ash tree quality, the age distribution of trees, and planting densities are uniform across municipalities.[13] We also hold these factors constant across public and private land within each municipality. We later use sensitivity analysis to introduce asymmetries between the two municipalities. For example, a lower planting density in one municipality can be captured by changing $b(q_I)$ in Eq. (20). Similarly, differences in planting densities across public and private land can be captured by a change in q_I, which may represent the proportion of trees on public land, rather than the proportion of land itself.

The Twin Cities span a land base of 274.4 km^2 and house a population of 716,049 residents (U.S. Census Bureau 2017). To aid in the interpretation of our results, we report them on a per-hectare basis, where each city is 13,720 ha. Tree surveys suggest that each city is home to approximately 250,000 green and white ash (*F. Pennsylvanica* and *F. Americana*), 30% of which are on public property (Kovacs et al., 2014; Minneapolis Parks and Recreation Board 2014; St. Paul Parks and Recreation 2015). We use nonmarket values published in the literature to calibrate the net benefits for uninfested trees, based on an estimated annualized non-market benefit of $94 for each ash tree (Sander et al. 2010). Nonmarket values from standing ash trees, and the net benefits that follow from them on public and private land for the infested and uninfested municipalities, are assumed to be pure public goods and include aesthetic beauty, shade, erosion control, groundwater filtration, or increases in home values due to large trees located on a property. Total nonmarket values on public and private land differ due to tree densities and estimated total number of trees from the literature. For 250,000 trees, for example, this suggests a maximum non-market benefit of $23.5 million per year for the uninfested municipality.

Table 1
Model notation and baseline parameter values.

Parameter	Description	Value
q_I, q_U	Public land ownership in each municipality (proportion)	0.30
$V_{I,public}(0)$	Net benefits public land, infested and treated with insecticide ($m/yr)	4.75
$V_{I,private}$, $V_{U,private}$	Net benefits private land, infested and treated with insecticide ($m/yr)	16.00
$V_{U,public}$	Net benefits public land, infested and treated with insecticide ($m/yr)	4.75
$\bar{V}_{U,public}$, $\bar{V}_{U,private}$	Net benefits, uninfested ($m/yr)	23.50
c	Linear parameter, net benefit of ash trees in infested municipality	−0.2727
d	Quadratic parameter, net benefit of ash trees in infested municipality	−0.0661
r	Growth rate in probability of spread	0.08
p_0	Initial probability of spread	0.50
a	Coefficient for indirect effect of transfers on spread	0.04
ρ	Discount rate	0.02
γ_i	Bargaining power coefficients	0.50

To calculate the costs of treatment, we use the estimated number of ash trees by diameter class in maintained urban areas from VanderSchaaf and Jacobson (2011) for the state of Minnesota. Based on the proportion of trees in each of four size classes (small, medium, large, and super) and the average diameter at breast height (dbh) for trees in each class, we calculate the associated annual treatment and removal costs using the EAB Management Cost Calculator from Urban Tree Alliance (2017). The average cost of removal and replacement is $760 per tree. The weighted average treatment cost for the professionally applied systemic insecticide emamectin benzoate in two-year cycles is approximately $75 per ash tree. When facing infestation, we assume that private landowners will treat their trees with a commercial granular or soil drench product at a cost of $30 per tree per year (Liesch et al., 2012).

If the infested municipality does not receive a transfer payment, we assume that public land managers will opt for the systemic insecticide treatment. Taken together with the non-market value of urban ash canopy, the annualized net benefits of ash trees on infested public land are $19 per tree ($4.75 million total). On private land in the infested municipality, the annualized net benefits of ash trees are $64 per tree ($16.00 million total). Consistent with our assumption that the municipalities are identical with respect to their ash tree stock, we assume that the same levels of net benefits apply in the uninfested municipality if it becomes infested.

We choose the growth rate in the probability of spread in Eq. (19) such that spread occurs with certainty within 10 years, which is similar to anticipated spread rates for EAB projected by Kovacs et al. (2014) under the status quo. As an initial probability of spread, we choose 50%, and for the intensive margin function in Eq. (20) we choose a scale parameter of $a = 0.04$. Throughout the simulation, we assume equal bargaining power for the two municipalities and a discount rate

[12] EAB was first detected in St. Paul and from there spread into Minneapolis, though infestation in Minneapolis has been confined predominantly to locations near the boundary between the cities. St. Paul has historically relied on targeted applications of a systemic insecticide rather than tree removal to treat EAB. We examine *ex post* the question of how bargaining may have been used to slow spread. However, even now increased tree removals and widespread use of the insecticide in St. Paul could delay spread into other areas of Minneapolis.

[13] Although detailed data on ash tree stocks do not exist for the cities individually, they are similar to one another in other respects, such as land area and population. Minneapolis is 139.78 km^2 with 413,651 residents (as of July 1, 2016); St. Paul is 134.63 km^2 with 302,398 residents. For the purposes of this analysis, we standardize our results assuming that each of the two cities is 137.2 km^2 (13,720 ha). More generally, assuming symmetry as a starting point in the simulation ensures that our results are driven not by relative size differences between the two municipalities, but solely by their initial infestation status. We relax this assumption in the sensitivity analysis.

of 2%.[14] In sensitivity analyses, we allow the proportion of public land to vary for both municipalities and we consider a range of values for a.

Solution method

Taken with the terminal condition in Eq. (9), the first-order conditions for the first-best problem in Eqs. (7) and (8) and for the bargaining problem in Eqs. (13) and (14) implicitly define the optimal paths for transfer payments from the uninfested to the infested municipality. To solve these sets of equations for the dynamic path of transfer payments, we express the equations in discrete time and add non-negativity constraints to ensure that $\tau(t) \geq 0$ and $0 \leq p(t) \leq 1$. We consider a time horizon of 10 years, which captures the timeframe over which EAB spreads to the uninfested municipality with probability one in the uncoordinated case.

The uncoordinated, or disagreement, outcome is characterized by zero transfer payments. Numerically solving this problem involves allowing the probability of spread to grow according to its intrinsic growth rate, r. For the first-best outcome, we solve simultaneously the system of equations in (7)–(9). Solution of the bargaining problem in Eqs. (13) and (14) requires that we simultaneously solve for the optimal path of transfer payments and the Hamiltonian weights, μ_I and μ_U. These weights are a function of the maximized value of the net gains to bargaining as defined in Eqs. (12a) and (12b). To solve this problem, we follow Ehtamo et al. (1988) by iterating over the Hamiltonian weights and the bargaining path of transfer payments until convergence. We obtain convergence to a squared error of 1×10^{-5} in eight iterations in the baseline simulation, with weights of $\mu_I = 0.446$ and $\mu_U = 0.561$. We examine the social costs associated with the uncoordinated and bargaining outcomes by evaluating the first-best value function in Eq. (6) for $\tau(t) = 0$ and $\tau^b(t)$, respectively.

Simulation results

The results of the numerical simulation with the baseline parameter values from Table 1 are presented in Table 2 and illustrated in Fig. 1. Table 2 includes the path of the probability of spread and transfer payments in the uncoordinated, first-best, and bargaining problems. In the uncoordinated problem, the path of spread grows from an initial level of 50% to 100% by period 9. In this problem, the infested municipality earns present value of net benefits equal to \$115.673 million (\$11,346/ha). The present value of expected net benefits for the uninfested municipality (which will become infested with probability one) amounts to \$139.058 million (\$10,135/ha).

In both the first-best and bargaining problems, the path of transfer payments decreases over time, driving the probability of spread to zero. However, the path of payments is steeper in the first-best problem than in the bargaining outcome. In the first-best problem, payments decline from \$17.374 million (\$1,266/ha) in period 1 to \$2.895 million (\$211/ha) in period 4.[15] The bargaining path begins at \$11.629 million (\$848/ha) in period 1 and ends at \$1.131 million (\$82/ha) in period 7. In both cases, the probability of spread is driven to zero, though spread is eradicated three periods sooner in the first-best than in the bargaining case. Though payments are initially higher in the first-best solution, total transfer payments are lower than in the bargaining outcome, totaling \$39.244 million (\$2,860/ha) versus \$41.249 million (\$3,006/ha).

Table 2
Main simulation results.

Time period	Uncoordinated	First-best		Bargaining	
	$p(t)$	$p(t)$	$\tau(t)$	$p(t)$	$\tau(t)$
1	0.540	0.289	17.374	0.372	11.629
2	0.583	0.135	12.246	0.263	9.598
3	0.630	0.039	7.426	0.173	7.689
4	0.680	–	2.895	0.102	5.894
5	0.735	–	–	0.049	4.207
6	0.793	–	–	0.015	2.622
7	0.857	–	–	–	1.131
8	0.925	–	–	–	–
9	1	–	–	–	–
10	1	–	–	–	–
Total transfer payments	–	39.244		41.249	
Net benefits, infested	115.673	141.598		146.829	
Net benefits, uninfested	139.058	171.080		163.720	
Net benefits, total	254.731	312.678		310.549	
Social costs	57.947	–		2.129	

Notes: All monetary values are in present value, in millions of USD (\$m.).

Both municipalities gain substantially in terms of net benefits in the first-best problem, relative to the uncoordinated case. In the first-best solution, the infested municipality earns net benefits of \$141.598 million (\$10,321/ha), an improvement of \$25.925 million (\$1,890/ha) over the uncoordinated outcome. Although the infested municipality loses the non-market benefits of its urban ash trees, it is more than compensated for that loss with the transfer payment. The uninfested municipality gains in the first best with an increase in net benefits of \$32.022 million (\$2,334/ha). Although this municipality pays out \$39.244 million in transfer payments, it gains from an increase in expected net benefits as the probability of spread is quickly driven to zero. In total, the first-best solution increases net benefits by \$57.947 million (\$4,224/ha).

The bargaining problem involves greater transfer payments spread over a longer time horizon. As a result, the infested municipality is able to retain its ash canopy for a longer time frame, which increases their net benefits from \$141.598 million in the first best to \$146.829 million in the bargaining outcome (an increase of \$381/ha). The uninfested municipality, on the other hand, loses relative to the first best because of this delay in reducing the probability of spread. The net benefits for this municipality are \$171.080 in the first best versus \$163.720 in the bargaining outcome (a loss of \$536/ha). As a result, total net benefits decline to \$310.549 million, which implies a social cost of \$2.129 million (\$155/ha). This level of social costs constitutes a 96.3% reduction relative to the level of social costs in the uncoordinated outcome.

Fig. 1 illustrates the first-best and bargaining paths of transfer payments, overlaid on the static contract region from Eq. (5). Prior to period 2, the upper limit for the contract region exceeds the lower limit for the contract region. If restricted to period 1, there is no transfer payment that ensures positive net gains from bargaining for both municipalities. By period 2 of the dynamic problem there exists a transfer payment that results in gains for both municipalities (illustrated with the grey cross-hatched region in Fig. 1). The agreement region grows over time as: 1) the expected benefits from control increase for the uninfested municipality due to growth in the probability of spread (the upper limit in Eq. (5) increases); and 2) as the present value of the costs of tree removal decline for the infested municipality due to discounting (the lower limit in Eq. (5) decreases). Fig. 1 illustrates that both the first-best and bargaining solutions involve higher transfer payments earlier in the problem's time horizon than would be feasible in a static context. Allowing for transfer payments over multiple years allows the municipalities to incur net losses in the first 3 periods of the problem in

[14] We conduct sensitivity analysis with respect to relative bargaining power between the municipalities, but do not report the results here in the interest of brevity. As bargaining power shifts in favor of the infested municipality, the path of transfer payments is larger and longer, with higher social costs under bargaining. Conversely, a shift in favor of the uninfested municipality leads to a shorter, smaller path of transfer payments and lower social costs.

[15] As a point of reference, 250,000 trees spread over 13,720 ha with a uniform planting density implies 18.2 trees/ha of which 5.5 are on public land. The minimum payment that the infested municipality could accept for removal of a tree, on average, is \$760 in removal and replacement costs plus the loss of \$950 in non-market net benefits (\$19 in net benefits into perpetuity at a 2% discount rate), for a total of \$1,710 for the average tree.

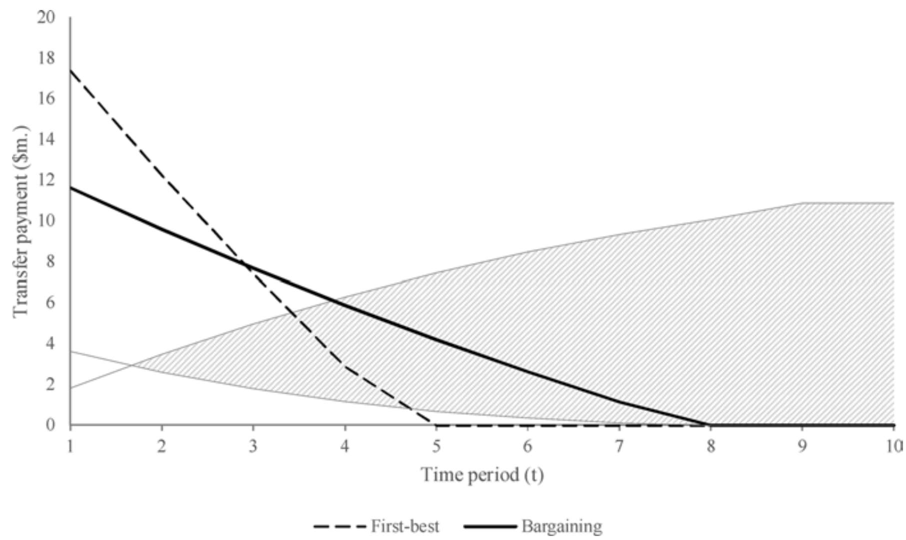

Fig. 1. Transfer payment path for first-best and bargaining problems.
Note: Static contract region is crosshatched in grey.

order to quickly reduce the probability of spread and maintain higher levels of net benefits in subsequent periods.

Public land ownership

Table 3 presents simulation results for a range of values in the proportion of public land in each municipality. For the infested municipality, reducing the proportion of public land from 30% to 10% reduces the length of the transfer payment path from 7 to 3 periods and increases the total amount of payments from $41.249 to $60.604 million (an increase of $1,411/ha). A decrease in q_I (the proportion of land in public ownership) increases the intensive margin effect, which increases the marginal efficacy of a dollar of transfer payments. This change pushes the bargaining path toward the first-best solution, reducing social costs to $0.234 million ($17/ha). The upper panel in Fig. 2 illustrates the increased slope of the bargaining path and the convergence of the bargaining and first-best paths of transfer payments. The figure also illustrates the effect of a change in q_I on the contract region, which is to reduce the lower bound from Eq. (5) and increase the incentive for the infested municipality to bargain.

The converse holds for an increase in q_I. An increase in public land from 30% to 50% generates an increase in the path of transfer payments from 7 to 8 periods, with a reduction in total transfer payments from $41.249 million to $35.561 million (a decrease of $415/ha). By reducing the intensive margin effect, an increase in q_I drives the bargaining path away from the first best and generates an increase in social costs to $8.608 million ($627/ha). Both municipalities see a decrease in net benefits, though the losses are disproportionately absorbed by the infested municipality. The infested municipality's net benefits decrease by 19.5%, while those of the uninfested municipality decline by only 4.9%. The lower panel in Fig. 2 illustrates the reduction in the slope of the bargaining and first-best paths of transfer payments, as well as their divergence from one another. An increase in the public land base reduces the incentive for the infested municipality to bargain, as illustrated by an upward shift in the lower bound of the contract region.

An increase in the proportion of public land to 70% in the infested municipality results in a reversion to the non-cooperative (disagreement) outcome. By examining the net benefits to the infested municipality in the last two columns of Table 3, the reason is clear. With 50% public land, the infested municipality earns net benefits of $118.201 million, which is a slim increase over the $115.673 million in net benefits earned in the disagreement outcome ($8,615/ha versus $8,431/ha). When the proportion of public lands in the infested municipality increases over a threshold level, no path of transfer payments exists that results in a net gain for the infested municipality under bargaining. With the baseline parameter values, this threshold value for public land is 65%.

Table 3 also presents results for a range of values in the proportion of public land in the uninfested municipality. Because public land requires more expensive treatment after the municipality becomes infested, the effect of this parameter is to increase the expected losses from becoming infested (an increase in $\overline{\Pi}_U(q_U)-\Pi_U(q_U)$). The result is an increase in the duration of transfer payments as well as their total. For example, moving from 10% to 90% public land in the uninfested municipality increases the duration of transfer payments from 6 to 10 years with an increase in transfers of $2.298 million ($167/ha). This

Table 3
Bargaining outcomes by proportion of public land ownership.

	Proportion public land, infested municipality			
	$q_I = 0.1$	$q_I = 0.3$	$q_I = 0.5$	$q_I = 0.7$
Ratio of Hamiltonian weights (μ_I/μ_U)	0.252	0.795	0.717	–
Years of transfers	3	7	8	–
Total transfer payments ($m.)	60.604	41.249	35.361	–
Net benefits, infested ($m.)	185.072	146.829	118.201	115.673
Net benefits, uninfested ($m.)	151.347	163.720	155.747	139.058
Net benefits, total ($m.)	336.420	310.549	273.948	254.731
Social cost ($m.)	0.234	2.129	8.608	57.947
	Proportion public land, uninfested municipality			
	$q_U = 0.1$	$q_U = 0.5$	$q_U = 0.7$	$q_U = 0.9$
Ratio of Hamiltonian weights (μ_I/μ_U)	0.471	1.106	1.415	1.729
Years of transfers	6	8	9	10
Total transfer payments ($m.)	40.350	41.850	42.303	42.648
Net benefits, infested ($m.)	144.920	147.899	148.632	149.158
Net benefits, uninfested ($m.)	168.663	159.041	154.404	149.846
Net benefits, total ($m.)	313.582	306.940	303.037	299.004
Social cost ($m.)	0.255	4.719	7.724	10.986

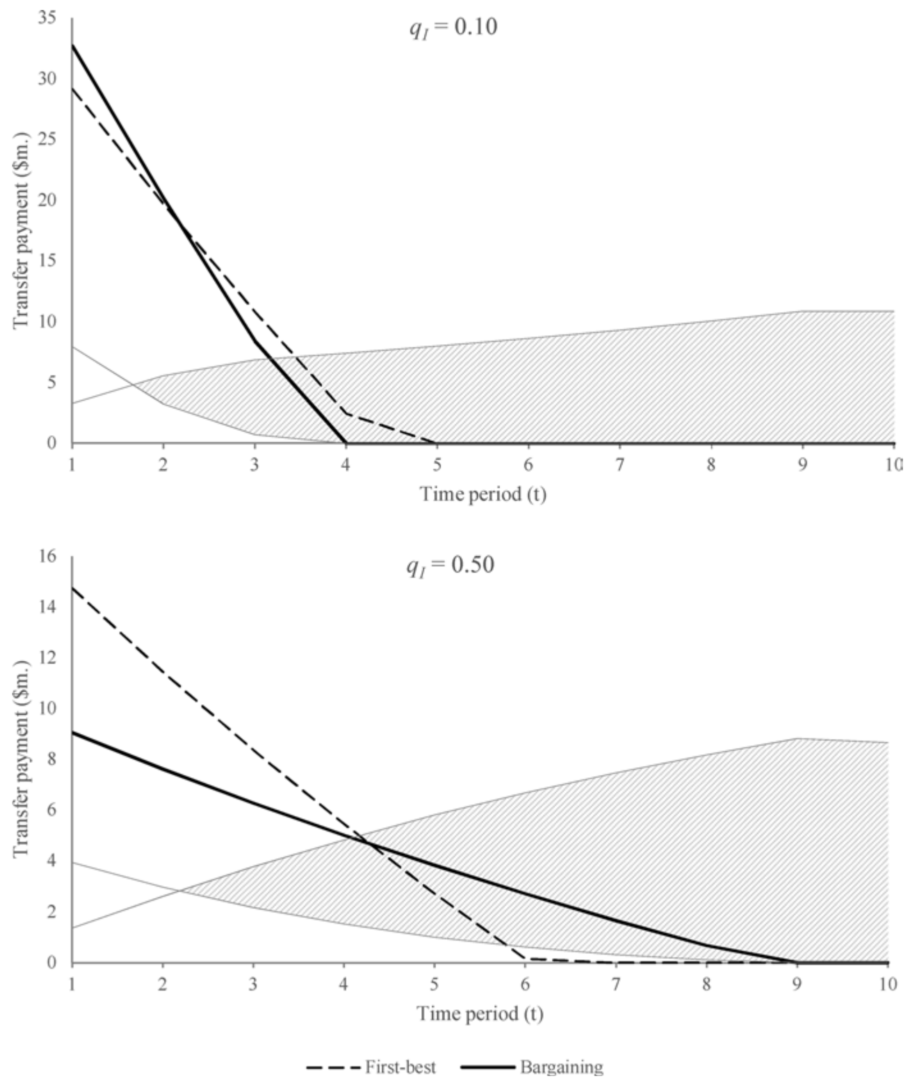

Fig. 2. Transfer payment paths for first-best and bargaining problems, by proportion public land in the infested municipality.
Notes: Upper and lower panels illustrate results with 10% and 50% public land in the infested municipality. Static contract region is crosshatched in grey.

change in transfers reduces expected net benefits to the uninfested municipality and increases social costs by $10.731 million ($782/ha).

Free riding on private land

It is informative to examine the sensitivity of results to free riding through the $b(q_I)$ function given its importance to the efficacy of a positive transfer payment in the probability of spread (see Eq. (1)), and the fact that this function is responsible for a non-monotonic change in the probability of spread as the proportion of public land q_I increases. As the infested municipality undertakes higher-intensity control on public land as part of a bargaining agreement, private landowners may free ride by reducing private expenditures on EAB control. The result of free riding on private land is to reduce the efficacy in slowing the probability of spread with a unit of transfer payment on public land. This is equivalent to a downward shift in the intensive margin effect, $b(q_I)$, as discussed in Eq. (1). To examine the effect of free riding in the simulation model, we consider a range of values for the parameter a in Eq. (20). A reduction in a from its baseline level of 0.04 captures an increase in the severity of free riding. Fig. 3 illustrates the intensive margin function for a range of values for a. An increase in a for a fixed proportion of public land increases the level and the slope of the intensive margin effect. Notice from the figure that the importance of free riding decreases as the proportion of public land increases relative to private land; as this proportion approaches one on the far right of Fig. 3, only the direct effect of the transfer payment in Eq. (1) matters as the higher controls are applied to 100% of the land that exists in the infested municipality.

Table 4 presents the bargaining outcomes for a range of values in a. As the severity of free riding increases and a decreases to 0.03, the bargaining outcome involves a shorter path of higher transfer payments. The net benefits to the infested municipality increase, while those for the uninfested municipality decrease. The net result of these changes is a decline in total net benefits and an increase in social costs. As free riding decreases (and a increases), the path of transfer payments is longer and lower, with smaller net benefits to the infested municipality and larger net benefits to the uninfested municipality. The magnitude of social costs changes nonlinearly as the first-best and bargaining outcomes change simultaneously with a. Fig. 4 illustrates the relative changes in the first-best and bargaining solutions for two values of a. As a increases, the bargaining path becomes shallower and longer while the first-best path becomes steeper and shorter.

Table 4 also illustrates the interaction between the intensive margin effect and the threshold for the percentage of public land above which agreement is not possible. In the baseline simulation, we find that a bargaining agreement is not possible above a threshold of 65% public land. As the severity of free riding increases (a decreases), this threshold falls. When a is 0.03, the threshold for public land is 40%; as a

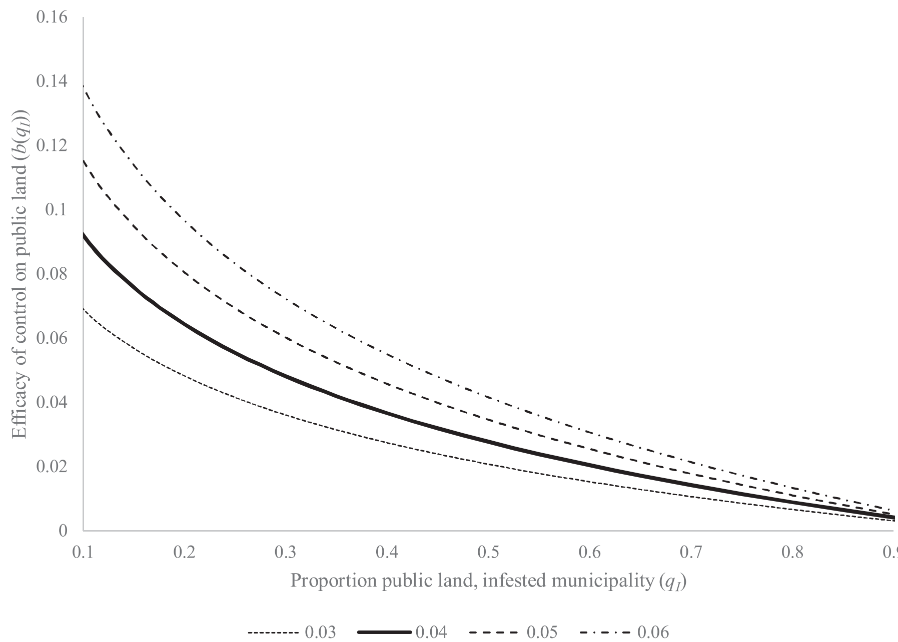

Fig. 3. Intensive margin effect of public land as a function of severity of free riding on private land.
Notes: Intensive margin effect of public land in the infested municipality is given by the function $b(q_I)$, where q_I is the proportion of public land in the municipality. The value for the parameter a scales the intensive margin effect based on the severity of free riding on private land, where a decrease in a reflects an increase in free riding. The baseline value for a in the simulation is 0.04 (illustrated with a solid black line).

Table 4
Bargaining outcomes by severity of free riding on private land.

	$a = 0.03$	$a = 0.04$	$a = 0.05$	$a = 0.06$
Ratio of Hamiltonian weights (μ_I/μ_U)	0.389	0.795	1.217	1.646
Years of transfers	6	7	8	8
Total transfer payments ($m.)	48.963	41.249	33.220	27.754
Net benefits, infested ($m.)	149.237	146.829	142.038	138.322
Net benefits, uninfested ($m.)	152.062	163.720	171.009	176.196
Net benefits, total ($m.)	301.299	310.549	313.047	314.519
Social cost ($m.)	3.460	2.129	4.128	5.541
Public lands threshold (%)	40	65	73	79

increases to 0.05 and 0.06, the threshold for public land increases to 73% and 79%, respectively. A reduction in free riding thus increases the range of cases for which bargaining is a viable mechanism to reduce the probability of spread across municipalities.[16] Conversely, an increase in free riding constrains the likely success of bargaining to cases in which the proportion of public lands in the infested municipality is relatively low. Fig. 4 illustrates the change in the contract region with an increase in a: a reduction in free riding increases the scope for a bargaining agreement by expanding the contract region. For larger values of a, the contract region expands to a point where there exists a transfer payment in period 1 that generates net gains for both municipalities. More severe free riding, however, implies that a multi-period bargaining framework is necessary to arrive at an agreement.

Conclusion

Invasive pest species that spread across boundaries using host trees are a common forest management problem. Local or municipal governments are often only able to apply controls to tree populations on public land holdings, but in many cases there is significant private land containing host trees that contribute to pest spread across borders. The proportion of public to private land is therefore critical in influencing the losses in net benefits expected from cross-boundary forest pests as well as the potential for their control. In these contexts, social costs are generated through two channels. First, an infested municipality in one location may not have incentives to incur control costs in a way that minimizes spread and losses in net benefits to adjacent uninfested municipalities. Second, private landowners have incentives to free ride on control efforts applied to public land in their location.

We examine scope for bargaining between adjacent governments in these problems as a mechanism to slow the spread of an invasive species across the boundaries of jurisdictions with mixed public and private land ownership. Bargaining arises through a transfer payment made from an uninfested municipality to an adjacent municipality in return for higher levels of controls that reduce spread probabilities through time. The proportion of public to private land plays an important role in whether a bargaining agreement is reached and the nature of the transfer payment from any agreement. It also plays an important role in comparisons between the first-best outcome under full cooperation and the bargaining outcome. While an increase in public land implies that the public land manager has access to a larger land base for control, it also means that a dollar of transfer payment to adopt higher-intensity control is spread over a larger land base. The result is a decrease in the marginal efficacy of the transfer payment in reducing the probability of spread. We demonstrate that this intensive margin effect reduces and extends the path of transfer payments in the bargaining solution. The consequence is an increase in the social costs of bargaining for an infested municipality with a larger public land base.

We also find that above a threshold in the proportion of public land, an infested municipality has no incentive to bargain. The result is a reversion to the disagreement outcome and the maximum level of social costs. Where this threshold sits is a function of the degree of free riding by owners of host trees on private land. When free riding is severe, it is not possible to reach agreement for control even for a relatively small public land base. As free riding becomes less problematic, bargaining becomes viable for municipalities with more public lands. Thus, the viability of bargaining is not simply a function of how much land is under the control of the public land manager; it is also a function of

[16] A change in $b(q_I)$ could capture other factors that influence the efficacy of transfer payments in limiting spread. For example, if ash trees are planted at lower densities on private land, the effect would be to increase $b(q_I)$ and increase the public land threshold.

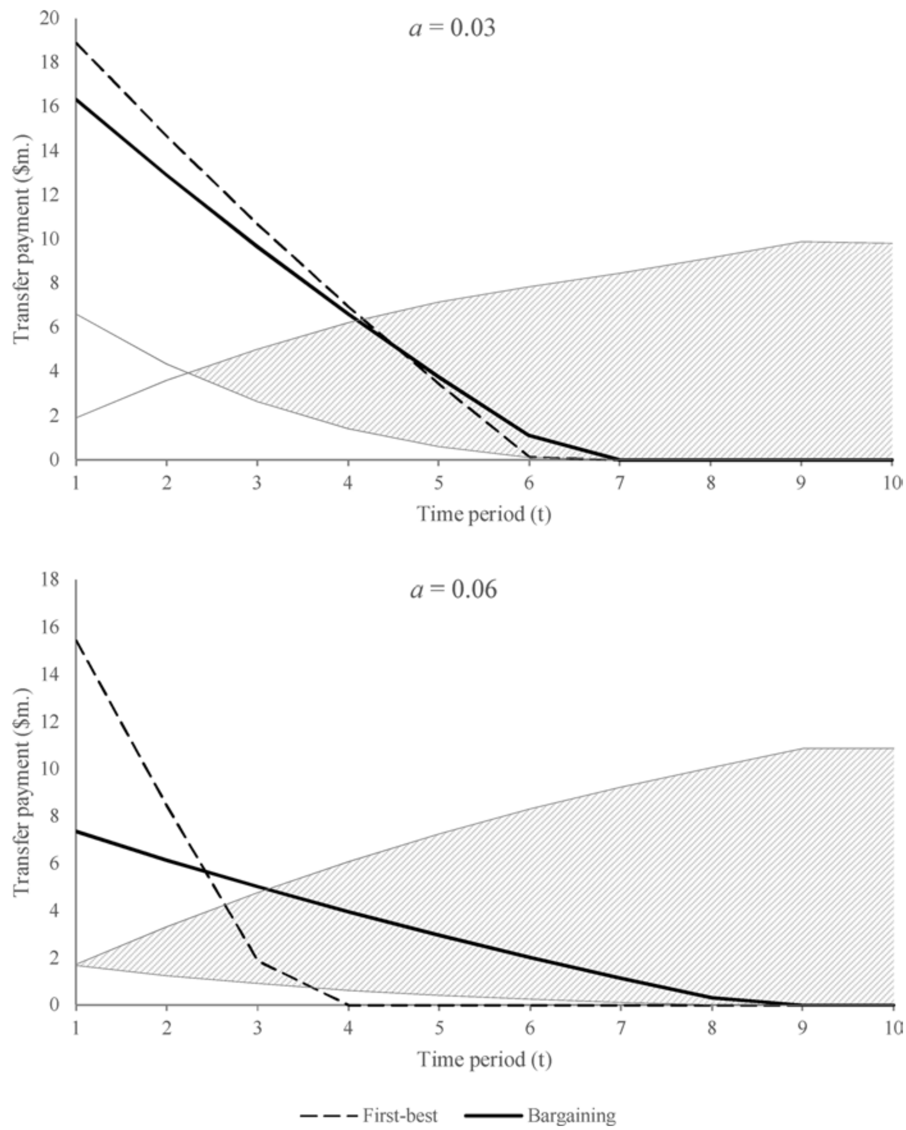

Fig. 4. Transfer payment paths for first-best and bargaining problems by severity of free riding on private land.
Notes: Upper and lower panels illustrate results for $a = 0.03$ and $a = 0.06$, where a decrease in a captures an increase in the severity of free-riding on private land. In both panels, the proportion of public land in the infested municipality is fixed at its baseline level of 30%. Static contract region is crosshatched in grey.

what happens on private land. If private landowners react to increased public intervention by reducing their control, the result is to undercut a bargaining agreement.

These findings provide insight for invasive forest species policy. The interaction between the intensity of control on public and private lands within a jurisdiction complicates efforts to control the spread of an invasive species across jurisdictions. A decentralized bargaining approach is most effective in jurisdictions with a smaller public land base and/or for those jurisdictions that are best able to guard against free riding. These factors also carry implications for the temporal nature of a bargaining agreement. In many cases, a bargaining agreement is only possible over a multi-year time horizon. In rare cases, a single-period agreement may be possible, but it will involve higher social costs than a multi-year agreement because it deviates substantially from the first-best dynamic outcome. Thus, bargaining is most likely to succeed in a policy environment that supports multi-period inter-jurisdictional agreements and guards against potential free riding by private landowners on the public control effort.

There are several ways our analysis could be extended. First, the probability of spread is highly pest- and location-dependent. In some cases, invasion of a pest across boundaries may be such that bargaining never would occur, either because the biological spread dominates any controls, or because the pest is present at a density that is too low to spread. Further, while our theory specifies general nonmarket values and resulting net benefits of healthy trees, our empirical section relies on published pure public goods value estimates for standing healthy ash trees. It is possible, however, that nonmarket values of trees on private lands are impure public goods or at least are not pure public goods by definitions. While the theoretical model accommodates this possibility, there is no published data or results on these differences between a tree on private land and a tree on public land. Our work here suggests that additional empirical efforts are needed to estimate the differences in these values relative to public lands values in order to inform future analyses of scope for cooperation for transboundary pests such as EAB. Finally, how private landowners react to government bargaining agreements and control actions should be more fully developed in future analyses. This is particularly true for EAB where private landowners would forego nonmarket benefits as they increased controls in the form of tree removal.

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