Spatial bioinvasion externalities with heterogeneous landowner preferences: A two-agent bioeconomic model

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Abstract

Preference heterogeneity among landowners managing transboundary resources can determine the production of externalities across their lands. We test this hypothesis in the context of an invasive species affecting two forest landowners where one values their property for recreation and the other produces timber. Using a spatially explicit first-mover repeated game, we find that the social cost of the externality is greatest when a bioinvasion starts on the recreation property. Except for species with fast long-distance dispersal, the optimal subsidy is nonuniform, targeting the landowner who acts as the weaker link, regardless of where a bioinvasion starts.

Key words: bioeconomics; ecosystem services; externalities; forest health; invasive plants; spatial-dynamic modeling.

JEL Codes: D62, Q23, Q57.

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Controlling invasive plants, pests, diseases, and fire is critical for the health of forest ecosystems and important for people who benefit from forest ecosystem services. These forest disturbances are mobile and renewable and can, therefore, lead to spatial-dynamic externalities if they are sub-optimally controlled from a landscape perspective. This may happen when the production and mitigation of such externalities depend on the private actions of many forest landowners and managers with different forest ownership motivations and management objectives. In the United States (U.S.), more than half of the forests are owned or managed by private parties that report owning and managing their forestlands for a diverse set of non-market ecosystem services (NMES) and market ecosystem services (MES): 35% of family forest landowners report owning their woodlots or forests for NMES, mostly recreation, 12% for MES, mostly supplemental income from timber, and 37% for a mix of NMES and MES (Butler 2008; USFS 2015).[i] In addition, most private forest landowners are above 65 years old, and many of them plan to transfer their land to their heirs or sell it (USFS 2015), which can lead to an increase in forest parcelization. As a result, forest management decisions might become spread across a larger pool of owners who have smaller properties and diverse forest ownership motivations, which can complicate the successful achievement of landscape-scale management of forest disturbances (Mehmood and Zhang 2001; Butler and Ma 2011). [ii] Studying the management of forest spatial-dynamic externalities in the context of such landownership patterns requires research frameworks that account for the decentralized management of cross-boundary public bads affecting properties managed by landowners with heterogeneous preferences.

The literature on the management of forest disturbances offers insights and management recommendations for the case of one manager making decisions over a landscape (e.g., Horie et al. 2013), one manager maximizing the utility of a representative household (e.g., Sims, Aadland, and Finnoff 2010), or one landowner maximizing net timber revenues from their property (e.g., Macpherson et al. 2017). Because bioinvasion control is a weaker-link public good (Burnett 2006), the control decisions of one landowner can decrease the returns to control for other landowners (Cornes 1993). Decentralized management can therefore have a strategic nature, which becomes especially important if preference heterogeneity drives which landowners act as the weaker links and contribute to the production of the spatial-dynamic externalities through their management decisions. Studies that address the effect of preference heterogeneity find that it can cause the privately optimal decisions to diverge among resource users, while ecological heterogeneity might delay the initiation of management decisions (Costello and Kaffine 2018). Preference and ecological heterogeneity are typically represented by differences in parameter values such as spread rates, control costs, or resource value (Atallah, Gómez, and Conrad 2017; Costello, Quérou, and Tomini 2017). Preference heterogeneity has also been considered along the lines of the terminal period MES revenues vs. periodic NMES flows, as opposed to differences in parameter values only (Dangerfield et al. 2016). In this context, differences in ecosystem service preference among forest managers can lead them to act at different times and potentially never adopt management strategies. Where ecological uncertainty is high and environmental damage, and mitigation investments are irreversible, it can be socially optimal that the first landowner(s) in the invasion "takes one for the team" by delaying mitigation, so the rest gain new information about the ecological process and capture the option value of delaying mitigation (Sims, Finnoff, and Shogren 2018).

The broad hypothesis of this article is the following: private forest landownership patterns that are characteristic of the Northern U.S. can act as drivers of bioinvasions and determinants of bioinvasion externalities at the landscape level. That is, preference heterogeneity among landowners managing ecologically-connected, transboundary resources can have a detrimental effect on the provision of public goods (Cornes 1993) and can determine the divergence between centralized and decentralized management payoffs (Oates 1972; Besley and Coate 2003).

To test this hypothesis, we develop a modeling framework that consists of a spatially explicit game where landowners on two neighboring properties make first-move invasive control decisions based on the arrival of the invasion. The invasive species connects heterogeneous landowners and their ecosystem benefits at two spatial scales, within and across land properties. This framework extends existing models of a single manager or household, models with multiple agents with homogeneous preferences or those that are heterogenous in cost or damages parameter values, models of heterogenous but ecologically-isolated landowners, and models where the bioinvasion dynamics and damages are simplified for tractable theoretical insights. Specifically, in our modeling framework, (1) landowners have heterogeneous preferences over the ecosystem services (ES) they value; (2) ecosystem service damages within and across properties can be spatially heterogeneous; (3) spatial connectivity occurs through short and long-distance dispersal of the invasive species; and (4) the strategic behavior is driven by the sequential arrival of the bioinvasion, spatial connectivity, preference heterogeneity, and non-uniform damages. In accounting for landowner preference heterogeneity, we consider the differences in how ES are produced, valued, and damaged over space and time. We develop and use spatially explicit, dynamic ES production functions. Conceptually, MES benefits such as timber revenues and damages are typically not spatially-dependent (i.e., timber values and the damage caused by an invasive species do not depend on where a tree grows on a property) and benefits are realized at a specific point in time (i.e., a timber harvest). In contrast, NMES benefits are periodic and can be produced and damaged in a spatially defined way (e.g., trail recreation) or non-spatial ways (e.g., air purification).

Multi-scale ecological spatial connectivity is especially important to recognize when modeling strategic behavior where agents' payoffs are connected by public bads that disperse through short-distance (SDD) and long-distance dispersal (LDD) mechanisms. In our model, the SDD mechanism operates at a smaller spatial scale and allows the representation of spatially non-uniform damages within a property. The LDD mechanism across properties operates at a larger spatial scale and therefore allows linking the ES damage functions across properties to produce landscape-level ES damage and production functions. Together, these dispersal patterns create multi-scale spatial linkages that go beyond considering the contiguous spatial unit only. Importantly, linking within and across property bioinvasion dynamics among heterogeneous landowners allows capturing the interacting effect of where the bioinvasion starts and which type (MES vs. NMES) of landowner moves first, on the social cost of the externality and the optimal subsidy.

We consider the case of glossy buckthorn in eastern white pine forests in the US. Glossy buckthorn (*Frangula alnus* P. Mill.) is a fast-growing shrub that is exotic and invasive in North America. It is one of around 20 non-native woody plants that have invaded eastern U.S. forests (Webster et al. 2006). Its moderate shade tolerance (Sanford et al. 2003; Cunard and Lee 2009) allows colonization of forest understories where it can form a dense, persistent layer affecting NMES such as recreation and wildlife habitat (Frappier et al. 2003; Fagan and Peart 2004; Cunard and Lee 2009; Lee and Thompson 2012; Koning and Singleton 2013). Through competition and shading, buckthorn affects MES provision by inhibiting the regeneration of economically important forest trees such as the eastern white pine, *Pinus strobus* L. (Fagan and Peart 2004; Frappier et al. 2004; Koning and Singleton 2013). Buckthorn recruitment and dispersal occur entirely from seed (Godwin 1943; Lee and Thompson 2012), which are dispersed through SDD and LDD by small mammals and birds, respectively (Godwin 1943; Catling and

Porebski 1994). After dispersal, germination, and establishment, landowners can identify glossy buckthorn seedlings and shrubs by their characteristic bark, twigs, leaves, flowers, and seeds. In the case of glossy buckthorn, cost estimates for this treatment range between $1,500 and 3,000/acre (Lee, 2017). According to a choice experiment with Maine and New Hampshire, family forest landowners willing to control glossy buckthorn are motivated by mitigating its effects on timber, trail recreation, and wildlife viewing (Atallah et al. 2023). While woody invasive plants can be controlled using chemical or mechanical methods such as repeated stem cutting (Cygan, 2014), respondents in that survey prefer mechanical methods and strongly oppose chemical methods when controlling the spread of glossy buckthorn. Finally, the general traits of glossy buckthorn, such as its moderate shade tolerance, short and long-distance dispersal mechanisms, effects on MES and NMES, and control methods, are shared with other forest invaders, such as Japanese barberry and Amur honeysuckle. In the *Sensitivity Analyses* section, we consider cases where the invasive shrub has slower and faster short and long-distance dispersal relative to glossy buckthorn.

Methods

We develop a tree-level model with two white pine forestlands, independently managed by two landowners, and invaded by glossy buckthorn. The shrub spreads within a property according to an SDD mechanism (i.e., seed fall from the shrub and mammal-mediated dispersal within a property) and across properties according to an LDD mechanism (i.e., bird flight). In the baseline preference heterogeneity case, Landowner *A* manages forestland for trail recreation, a spatially produced NMES, and perceives the negative impact of the invasive plant on the trail recreation value of their trees in a spatially explicit way. Landowner *B* manages their private pine forest to produce timber and perceives the negative impact of the invasive plant on timber volume through the inhibited or delayed regeneration and growth of juveniles. We also consider two preference homogeneity cases where both landowners have similar MES or NMES preferences. We solve for the optimal bioinvasion control timing and intensity for each landowner in a sequential, repeated game setting, subject to the invasion dynamics within and across their forestland, and subject to bioinvasion control of the other landowner. We solve the problem for the cases where landowners have homogeneous and heterogeneous preferences, and where they are affected first or second by the bioinvasion. Landowners decide on an optimal time-path which consists of different actions and intensities in different years. Their control decisions are time-variant both within a game stage and across game stages. We also solve the problem from the point of view of a central planner or the sole owner of the two forestlands.

We simulate the bioinvasion process in discrete space and time by modeling each forest tree as a cellular automaton. Using cellular automata allows modeling the ES production and damage functions, and the NMES benefits, in a spatially explicit and dynamic way. Each cell stochastically updates its invasion states (uninvaded, invaded at increasing levels) in discrete time steps based on the invasion state and distance to contiguous and noncontiguous cells to which it is ecologically connected through SDD (Atallah et al. 2015; Epanchin-Niell and Wilen. 2012) and LDD mechanisms (Atallah, Gómez, and Conrad 2017; Hall et al. 2017), respectively. The LDD mechanism has an exogenous component representing new random arrivals from outside the modeled landscape (LDD1) and an endogenous component that is distance and density-dependent, representing bird dispersal from within the modeled landscape (LDD2) (Fig. 1). A landowner perceives the consequences of the actions of their neighbor through this LDD2 process. Depending on the landowner preferences, the ES value of a tree evolves over time based on its bioinvasion state, location (e.g., on a recreation trail), diameter state (i.e., timber volume), and age state (i.e., timber quality).

A Bioeconomic Model of Externality Dispersal and Control

The bioinvasion disperses on a network composed of two grids managed independently (decentralized management, or DM) or jointly (central planner management, or CP). The grids represent forestlands of landowners *A* and *B* and are linked through the SDD and LDD of the invasive plant. Landowner *A*'s recreation value is the product of their consumer surplus (CS) per recreation day and their average user days (UD) (Walsh and Olienyk 1981; Rosenberger et al. 2013). Both CS and UD are quadratic functions of the longest connected sub-network composed of uninvaded trees, representing an accessible forest recreation trail. In the *Sensitivity Analyses* section, we consider the case of other, non-recreation NMES. The bioinvasion affects Landowner *B*'s net revenues through the inhibited or delayed growth of young trees in invaded stands: adult trees are not affected, but their ability to regenerate is inhibited or delayed based on whether control takes place in the form of the mechanical removal of the shrub. The control by each landowner determines their net benefits and those of the other landowner because they are connected through a biophysical network of invaded and uninvaded trees.

Grid G_A represents forestland *A* and is the set of $I*J$ cells denoted by their row and column position (i, j). Each cell (i, j) represents a pine tree. Similarly, grid G_B represents forestland *B* and consists of $M*N$ cells denoted by their row and column position (m, n). Each pine tree updates its age-diameter (i.e., timber yield and quality) and infestation states in discrete time steps (t) based on its own current age-diameter and infestation state and the infestation state of its neighbors (i.e., SDD process), that of non-neighboring pine trees (i.e., LDD2 process), and random arrivals of dispersed seeds from outside the landscape (i.e., LDD1 process). Each tree's infestation state transitions are governed by a discrete-time Markov chain model (i.e., the probability distribution of the next state depends only on the current state and not on the sequence of events that precede it). A tree in a cell (i,j) or (m,n) and state *Healthy (H)* transitions to state *Invaded-*

undetectable (I_u) once seeds are dispersed to it, and they successfully germinate. This transition probability depends on the number and location of invaded pine trees on the landscape. This state is unobservable to the landowner because it consists of seed arrival and germination with no recognizable above-ground plant parts. Subsequently, a tree transitions to the third state *Invaded-detectable* (I_u), which is only observable to a landowner who conducts surveillance and is trained to identify the characteristic stem and leaves of the shrub. The transition to state *Invaded-moderate* (I_m) and later to state *Invaded-high* (I_h) occurs as the invasive plant grows, forms a clump, and produces berries that can then be dispersed to the landscape via the SDD and LDD2 processes. In the baseline model, we consider that landowners can only observe states *Invaded-moderate* (I_m) and *Invaded-high* (I_h). In the *Sensitivity Analyses* section, we consider the case of surveillance and early detection where landowners are trained to identify and treat trees in state *Invaded-detectable* (I_u).

An externality emerges when the privately optimal management strategy in one forestland is lower than optimal from a landscape perspective, which causes the bioinvasion to spread to the neighboring parcel, thus affecting the neighboring landowner's net benefits (Fig. 1). We describe next the landowners' private net benefit maximization problems and the externality dispersal model.

[Insert Fig. 1 here]

Economic Model

Each landowner's objective is to maximize the present value of net benefits by choosing a time-varying invasive plant control strategy, $\mathcal{W}_t$. The optimal control strategy $\mathcal{W}_t^*$ is a set of cell-level control variables $\{z_{i,j,t}\}$ equal to 1 if control (i.e., invasive plant removal through repeated stem cutting) takes place in cell (i,j) and year t, and 0 otherwise. For the baseline model description, we assume that landowner *A* has NMES preferences, and landowner *B* has MES preferences. We consider later situations where they both have MES or NMES preferences. For simplicity of notation, we limit the model description to one game stage here and describe the sequential, repeated game in the section titled *Decentralized Management and Central Planner Problems and Solution Procedures*.

The objective of Landowner *A* is to choose the set of binary control variables $\mathcal{W}_t$ that maximize the following expected discounted sum, over 25 years (T), of net recreation values, where ρ is a yearly discount factor:

$$\max_{\mathcal{W}_t} \mathrm{E} \sum_{t \in T} \rho^t \left\{ CS\left(\sum_{(i,j)}^{G_A} v_{i,j,t} \right) * UD\left(\sum_{(i,j)}^{G_A} v_{i,j,t} \right) - c_A \sum_{(i,j)}^{G_A} z_{i,j,t} \right\} \quad [1]$$

$$\text{subject to } \mathrm{E}(\boldsymbol{s}_{i,j,t+1}) = \mathbf{P}^{\mathrm{T}} \boldsymbol{s}_{i,j,t} \quad [2]$$

$$\text{where } v_{i,j,t} - v_{i+1,j,t} = v_{i,j,t} - v_{i,j+1,t} = 0 \ \forall \ (i,j) | v_{i,j,t} = 1 \quad [3]$$

In Eq. (1), as in previous theoretical (e.g., Koskela and Ollikainen 1999) and empirical (e.g., Walsh and Olienyk 1981; Rosenberger et al. 2013) models of forest recreation, consumer surplus is a concave function of the recreation services or the trees providing these services. We follow empirical work (Walsh and Olienyk 1981; Rosenberger et al. 2013) to represent the total recreation value as the product of consumer surplus (CS) per day and the average user days (UD), which are contingent on the number of healthy trees. However, to recognize that bioinvasion damages can be spatially non-uniform, we model the ES damages and, as a result, the recreation ES production function in a spatially explicit way. Accordingly, in Eq. (3), for any healthy tree ($v_{i,j,t} = 1$) to count as part of a recreation trail in period t, both of its neighboring trees on that trail ($v_{i+1,j,t}$ and $v_{i,j+1,t}$) need to be healthy. This spatially-explicit damage is different from that of an invasive species on an NMES such as air purification where the location of the damage does not matter for the benefits, but only the total number of live trees does (e.g., Walsh and Olienyk 1981; Rosenberger et al. 2013). In the *Sensitivity Analyses* section, we relax this constraint to consider the case of non-recreation NMES. The CS and UD terms of the net benefit function are quadratic in the trail length. Mathematically, $CS\left(\sum_{(i,j)}^{G_A} v_{i,j,t}\right) = a_0 + a_1 \sum_{(i,j)}^{G_A} v_{i,j,t} + a_2 \left(\sum_{(i,j)}^{G_A} v_{i,j,t}\right)^2, a_0 < 0, a_1 > 0, a_2 < 0$ is the consumer surplus per recreation day and $UD\left(\sum_{(i,j)}^{G_A} v_{i,j,t}\right) = b_0 + b_1 \sum_{(i,j)}^{G_A} v_{i,j,t} + b_2 \left(\sum_{(i,j)}^{G_A} v_{i,j,t}\right)^2, b_0 < 0, b_1 > 0, b_2 < 0$, is the average user days. In Eq. 1, $z_{i,j,t} = 1$ if control takes place in cell (i,j) in year t with unit treatment cost c_A and zero otherwise.[iii] In equation (2), $v_{i,j,t} = 1$ if cell (i,j) is in state *Healthy* in year t and 0 otherwise. Equation (3) is the bioinvasion equation of motion, specified as a cell-level infestation state transition equation where $\boldsymbol{s}_{i,j,t}$ is the infestation state of cell (i,j) in period t, and **P** is the infestation state transition matrix defined in the following section. Because it incorporates the LDD2 mechanism, this infestation state transition captures the effect of the neighbor's actions.

Landowner *B*'s benefits are from timber revenues, which are a linear function of the number of pine trees, their age-diameter, and timber values, realized in year T.[iv] The objective of a landowner of type *B* is as follows:

$$\max_{w_t} E \sum_t^T \rho^t \sum_{(m,n)}^{G_B} (r_{d,m,n,t} - z_{m,n,t}\, c_B) \qquad [4]$$

subject to $\mathrm{E}(\boldsymbol{s}_{m,n,t+1}) = \mathbf{P}^{\mathrm{T}}\, \boldsymbol{s}_{m,n,t}$. [5]

In Eq. (4), revenue $r_{d,m,n,t}$ in cell (m,n) in year *t* depends on timber yield $y_{m,n,t}$, which depends on tree age (*Juvenile*, *Young*, *Mature*): $r_{d,m,n,t} = 0$ for *Juveniles*, $r_{d,m,n,t} = p\, y_{m,n,t}$ for *Young* and *Mature* trees. *Juveniles* have no commercial value while *Young* and *Mature* trees command net price p and produce yields $y_{m,n,t,young}$ and $y_{m,n,t,mature}$, respectively, where $y_{m,n,t,young} < y_{m,n,t,mature}$. The transition from *Juvenile* to *Young* occurs after τ_{young} years if a tree in cell (m,n) is *Healthy* and the eight immediately neighboring trees are *Healthy* too. The *Juvenile* tree does not transition to *Young* unless the invasive shrub is removed, which represents the process by which the invasive shrub can inhibit natural regeneration. The transition from *Young* to *Mature* occurs after τ_{mature} years and is not impacted by the bioinvasion (because the shrub cannot shade *Young* trees). The damage of the bioinvasion for G_B occurs through the inhibition of the transition from age-diameter state τ_{young} to age-diameter state τ_{mature} in the absence of control and through the delay of this transition depending on whether, how much, and when control takes place in cell (m, n) and in its immediate neighborhood. As opposed to the NMES case, we assume that the MES damage is not spatially explicit (i.e., the MES value of a tree and bioinvasion damages do not depend on its location on the forestland). As in Eq. (1), $z_{m,n,t} = 1$ if control takes place in cell (m, n) in period t with unit treatment cost c_B and zero otherwise. We define model parameters and report their baseline values in Table 1.

[Insert Table 1 here]

Model of Spatial-Dynamic Externality Dispersal

The invasive plant is introduced to the forestlands by bird-dispersed seeds according to a recurrent random exogenous long-distance dispersal event (LDD1). Subsequently, a transition from state *Healthy (H)* to state *Invaded-undetectable* (I_u) occurs according to probability α_1 that drives both the SDD and LDD2 dispersal processes (Eq. 6 and Eq.7). According to the SDD process, in each time step, a *Healthy* pine tree can receive invasive plant seeds at time *t+1* from any of its eight neighboring trees if they are in state *Invaded-moderate* or state *Invaded-high* (i.e., rate $N\alpha$ in Eq. 7 where N is the number of neighboring invaded trees). Seeds successfully germinate if $u_t < 1 - e^{-\alpha}$ and do not germinate if $u_t \geq 1 - e^{-\alpha}$, where u_t is a random draw from $U\sim$ (0, 1). An LDD mechanism that is endogenous to the model (LDD2), causes trees in state *Healthy (H)* to transition to state *Invaded-undetectable* (I_u) with a distance and density-dependent probability with rate $\gamma_{B,A,t}$ (Eq. 7).

The transition to states *Invaded-detectable* (I_d), *Invaded-moderate* (I_m), and *Invaded-high* (I_h) occur with probabilities α_2, α_3, and α_4, respectively. We define these probabilities and their associated parameters in Table 1. First, we focus on probability α_1, which drives the distance and density-dependent specification of the externality. This probability depends on the number and location of trees in state I_m or I_h within the same forestland and those in the neighboring parcel. The distance and density-dependence of this probability capture the impact of a landowner's private bioinvasion control actions, within their parcel, on the spatial damages borne by their neighbor at the border of and within the adjacent parcel. The transition matrix **P** in Eq. (3) and Eq. (5) govern the SDD and LDD mechanisms. It can be expressed as follows:

$$\mathbf{P} = \begin{pmatrix} (1-\alpha_1) & \alpha_1 & 0 & 0 & 0 \\ 0 & 1-\alpha_2 & \alpha_2 & 0 & 0 \\ 0 & 0 & 1-\alpha_3 & \alpha_3 & 0 \\ 0 & 0 & 0 & 1-\alpha_4 & \alpha_4 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix} \quad [6]$$

In Eq. (6), limiting the notation to G_A for exposition purposes, α_1 can be expressed as:

$$\alpha_1 = \Pr\left(s_{i,j,t+1} = I_u \,\middle|\, s_{i,j,t} = Healthy;\ s_{\mathrm{N}_{i,j,t}}\right) = 1 - e^{-(\alpha N_{i,j,t} + \mathcal{E}_t + \gamma_{B,A,t})} \quad [7]$$

Probability α_1 is determined by the SDD (i.e., $\alpha N_{i,j,t}$ term), LDD1 (i.e., $\mathcal{E}_t$ term) and LDD2 (i.e., $\gamma_{B,A,t}$ term) mechanisms. Parameter α represents the rate at which seed arrival and germination occurs in a cell (*i, j*). In each time step, seed arrival in a cell leads to germination and establishment if $1 - e^{-\alpha}$ is greater than a random draw from $U \sim (0, 1)$. The SDD term also depends on the state of the SDD neighborhood of cell (*i,j*), which is denoted by $N_{i,j,t}^{SDD}$ and describes the number of cells in the immediate neighborhood that can act as a bioinvasion source (i.e., in state I_m *or* I_h). Accordingly, $N_{i,j,t}^{SDD} = \{0 \ldots 8\}$ and the first term of the exponential rate will have $\{0, \ldots 8\alpha\}$, depending on the number of immediate neighbors that are in state I_m or I_h. The LDD2 mechanism in Eq. (7) is represented by the dynamic rate $\gamma_{B,A,t}$, which is a power-law dispersal parameter specified by the spatial-dynamic, distance- and density-dependent dispersal function defined in Eq. (8a) (Atallah, Gómez, and Conrad 2017). Indicator variables x and y, which equal 1 if a pine tree in row m and column n is in state *Invaded-moderate* (I_m) *or Invaded-high* (I_h) and 0 otherwise, are used to calculate the total number of invaded pine trees in each period that contribute to the LDD2 process from G_B to each cell in G_A. If $x = 1$, the corresponding forestland rows that have $y = 1$ contain pine trees in state $I_m$or I_h that contribute to the LDD2 from G_B to G_A. If $x = 0$ for all columns n (i.e., there are no cells on G_B that have glossy buckthorn producing berries that can be dispersed to G_A), $\gamma_{B,A,t}$ is not defined, and no dispersal occurs from these columns.

$$\gamma_{\mathrm{B,A},j,t} = j^{-\gamma \frac{\sum_n^N x \sum_m^M y((x,y) | s_{m,n,t} = \{I_\mathrm{m}, I_\mathrm{h}\}) * x}{\sum_n^N x\, M(N-x+1)}}, \gamma > 0, \sum_n^N x\, M(N - x + 1) > 0 \qquad [8a]$$

The transition rate $\gamma_{\mathrm{B,A},j,t}$ is inversely proportional to the distance from the bordering column (i.e., distance from column *j* on G_A to column N on G_B, regardless of its row position in column *j*). We choose a power-law specification because it allows the bioinvasion LDD to have new foci emerging beyond the bioinvasion front, which is appropriate for modeling bird-mediated seed dispersal. Dynamic parameter $\gamma_{\mathrm{B,A},j,t}$ is also proportional to the total number of pine trees that are in state $I_\mathrm{m}$or I_h on G_B, weighted by their column position *j* (the numerator in Eq. 8a) so that invaded cells closer to the bordering column contribute more to the externality than cells situated farther from the boundary.

Similarly, dispersal from G_A to G_B is given by:

$$\gamma_{\mathrm{A,B},n,t} = (N-n)^{-\gamma \frac{\sum_i^I x \sum_j^J y((x,y) | s_{i,j,t} = \{I_\mathrm{m}, I_\mathrm{h}\}) * y}{\sum_j^J y\, I(J-y+1)}}, \gamma > 0, \sum_j^J y\, I(J - y + 1) > 0 \qquad [8b]$$

This specification of LDD2 is adapted from the externality specification in Atallah, Gómez, and Conrad (2017), the only differences being the cell neighborhood type and the addition of the LDD1 term, and is in contrast with fixed externality dispersal rates or dispersal from cell to cell only that are common in the extant resource and environmental economics literature.

Bioinvasion and economic parameters are presented in Table 1 and Fig. 1.

Model Initialization

All pine trees are initialized as *Healthy*. In each forestland G_A and G_B, half of the trees are initialized in the *Juvenile* state and half in the *Mature* state, reflecting a mixed-age forest structure. At the first timestep and the beginning of each year, 2% of each parcel are invaded through an exogenous inflow of the invasive plant's seeds (LDD1, or ε_t in Eq. 7). That is, cells in each grid are chosen at random to transition from state *Healthy* to state *Invaded-undetectable*. Subsequently, the invasive plant grows, and the affected trees transition to *Invaded-detectable*. In this state, the invasive plant produces seeds that can be dispersed to neighboring and non-neighboring cells according to Eq. (3) and Eq. (5), and the dispersal occurs both within (SDD) and between (LDD2) forestland parcels.

The Decentralized Management and Central Planner Problems and Solution Procedures

We first solve the decentralized management (DM) problem as a forward-looking, noncooperative, five-stage, sequential, repeated game. In each game stage, a landowner decides on the timing and intensity of bioinvasion control that maximizes their expected discounted net benefits as defined in Eq. 1 and Eq. 4. Landowners make their bioinvasion decisions public and consider each other's decisions when sequentially making their own. The bioinvasion starts on one forestland, and the landowner affected first makes bioinvasion control decisions on the timing and intensity of bioinvasion control over the entire time horizon, taking into account that, in Stage 1, there is no bioinvasion and, therefore, no control on the neighboring forestland. In Stage 2, the bioinvasion arrives at the neighboring forestland (at a level that depends on the control actions of the first landowner), and the second landowner makes bioinvasion control decisions on the timing and intensity of bioinvasion control on their property for the remaining time horizon, taking into consideration the other landowner's stated plan for future bioinvasion control. The game is repeated in Stages 3, 4, and 5, representing five years each and a time horizon of 25 years. To illustrate, in a repeated game where the bioinvasion starts on G_A and A moves first, A moves at t=1 and makes a discounted expected net benefit maximizing management plan for the entire time horizon. At t=6, B moves and makes a management plan for the remaining time horizon (t=6 to 25), considering landowner A's previous actions and their stated plan for the remaining time horizon. At the beginning of Stages 3 (t=11-25), 4 (t=16-25), and 5 (21-25), each landowner updates their optimal time path taking into consideration past payoffs and updated future control plan of their neighbor. This game setting assumes that players share information by making their bioinvasion management plan known to the other player, and abide by it within each stage, but can change the plan for the subsequent stages.

Second, we solve the central planner's problem (CP). We consider the case of a fully-informed central planner who values the sum of the net benefits by landowners A and B and determines the timing and intensity of invasive shrub removal in forestlands G_A and G_B. In this sense, the central planner solution here also represents the point of view of the sole owner of both forestlands or that of the collective management of both forestlands. The CP solution achieves, from a landscape perspective, the optimal level, location, and timing of control by accounting for bioinvasion externalities across the two forestlands. The CP chooses two sets of bioinvasion management strategies, $\mathcal{W}_t^A$ and $\mathcal{W}_t^B$, one for each forestland, that maximize the present value of total expected payoffs, π_{CP}, defined as the sum of the present value of expected payoffs of G_{A} and G_{B}, π_A and π_B, respectively. [v] The CP solves the following maximization problem, subject to Eq. (2), Eq. (3), and Eq. (5).

$$\max_{(w_t^A,\ w_t^B)} \mathrm{E}(\pi_A) + \mathrm{E}(\pi_B) \qquad [11]$$

We define the social cost of the externality between the two forestlands as the difference between the central planner expected payoff, $\mathrm{E}(\pi_{\mathrm{CP}})$, and the aggregate expected noncooperative payoff ($\mathrm{E}(\pi_{\mathrm{T}}^{\mathrm{NC}}) = \mathrm{E}\ (\pi_{\mathrm{A}}^{\mathrm{NC}}) + \mathrm{E}\ (\pi_{\mathrm{B}}^{\mathrm{NC}})$. We consider the effect of subsidies and rank them based on the net aggregate payoff they generate, which we define as aggregate payoff net of total subsidy costs (i.e., unit subsidy multiplied by the realized total amount of control).

We obtain the optimal timing and intensity of control using a metaheuristic optimization engine, OptQuest, which uses an algorithm combining Tabu search, scatter search, integer programming, and neural networks (Kleijnen and Wan 2007). (Tabu search helps avoid the trap of local optimality.) For each landowner and the central planner, we report the optimal expected value and standard deviation for the net benefits and the number of treatments, obtained from 100 simulation runs. Outcome realizations for a given run within a Monte Carlo simulation differ by the random location of initial arrivals of the bioinvasion, the random location of the yearly exogenous arrivals (i.e., LDD1 process), and the random success of seed germination and establishment conditional on arrival within (i.e., SDD process) and between (i.e., LDD2 process) forestlands. The simulation and optimization models are written in Java using the AnyLogic software, which integrates the OptQuest optimization engine.

Results and Discussion

We first present the cases where landowners have the same preferences (i.e., preference homogeneity case) and follow with the case where they each have either NMES or MES preferences (i.e., preference heterogeneity cases). We then present the results on the effect of a bioinvasion control subsidy on aggregate payoff in the preference heterogeneity case. We finally present parameter and structural sensitivity analyses results that represent the cases of faster and slower short and distance dispersal, the case of non-recreation NMES benefits, and the case of surveillance and early detection.

Externalities under the preference homogeneity case

When both landowners are of the NMES type, none of them controls the bioinvasion in a repeated sequential game (Table 2). Expectedly, in the absence of control, the payoff is lower on the forestland where the bioinvasion starts even though they value the resource similarly and face the same damages and control costs. In contrast to the NMES landowner's no control strategy, a CP's optimal strategy is to control continuously on both forestlands, starting control simultaneously on both parcels but at a higher intensity where the bioinvasion starts (783 vs. 682 treatments; Table 2).[vi] The DM aggregate payoff is 48% lower than that of a CP's and is caused by the landowners' privately optimal decisions not to control (Table 2). This result of no control by the NMES landowner is driven in part by the magnitudes of the bioinvasion damages (constraint in Eq. 4 and equation of motion in Eq. 5) and control costs.

[Insert Table 2 here]

When both landowners are of the MES type, they each control the bioinvasion in Stage 3 (years 13 and 14) and Stage 4 (years 15 to 20) (Fig. 2). The control timing of the MES landowners is determined by their net benefit and damage functions: their objective is to maximize profits by 'freeing' young trees from the invasive shrub so that they can reach the higher-valued mature age classes. The DM aggregate payoff is 11% lower than that of a CP's (Table 3). While the 48% difference between CP and DM in the case where both landowners have NMES preferences stems from under-control (Table 2), the 11% difference here stems from overcontrol (2,165 vs. 1,688 treatments; Table 3), which is caused by the sequential nature of the DM case and the resulting misalignment of the timing of control on both forestlands, despite their identical preferences. Landowners update their plans in response to the realized plan of their neighbor, which results in increases in their payoffs compared to their expected payoffs at the beginning of the game. For example, updating strategies as a result of the repeated nature of the interaction decreases the CP-DM difference from 29% (in Stage 1, not shown in Table 3) to 11% (by Stage 5) in the case of a repeated game with two MES landowners.

[Insert Table 3 here]

[Insert Fig. 2 here]

Externalities under the preference heterogeneity case

In the preference heterogeneity case, we consider that landowner *A* has NMES preferences, and landowner *B* has MES preferences. When the bioinvasion starts on G_A and *A* moves first, the DM solution consists of *A* not controlling at all and *B* controlling the invasive plant in years 14, 15, and 23 (Fig. 3a, panel 1) at a level that is higher than that of the CP's (1,543 vs. 689 treatments; Table 4, panel b; Fig. 3a, panel 1 vs. panel 3). Landowner *A* overcontrols relative to the CP because of landowner *B*'s absence of control in a DM setting. Both *A*'s and *B*'s actions are consistent with their actions under the preference homogeneity cases where *B* controls and *A* does not (Tables 2 and 3). The social cost of the externality generated by *A*'s absence of control is $7,591 for the two acres (Table 4, panel b), a value that is statistically different from zero at the 1% level. The DM aggregate payoff is 40% lower than that under a CP case. Note that landowner *A*'s absence of control is due to the bioinvasion dispersal across properties. That is, when forestlands G_A and G_B are ecologically isolated (i.e., no LDD2), landowner *A* controls as much as landowner *B* does (Table 4, panel a).

[Insert Table 4 here]

[Insert Fig. 3 here]

When the bioinvasion starts on G_B and *B* moves first, landowner *B* controls earlier (year 11 vs. 14; figure 3b, panel 1) and less intensely (785 treatments in Table 4, panel c vs. 1,543 treatments in panel b) than they do in the case where landowner *A* moves first. The change in the first move order affects the social cost of the externality which is reduced by 31% (from $7,591 to $5,187; Table 4, panels b and c) and the aggregate payoff increases by 7% (from $11,263 to $12,060; Table 4, panels b and c). Landowner *B*'s first move confers benefits at the landscape level through bioinvasion control on their property, that consist of an increase in landowner *A*'s payoff from $831/acre (Table 4, panel b) to $1,569/acre (Table 4, panel c) even if no control occurs on G_A in either case. The increase in landowner *A*'s payoffs amounts to $797/acre and is statistically different from zero at the 1% level. The DM aggregate payoff is 30% lower than that of a CP, compared to 40% in the case where the bioinvasion starts on G_A and *A* moves first. In sum, the social cost of the externality is lowest when the MES landowner is affected first, in which case they control earlier and, therefore, less intensely than when they move second.

The effect of preference heterogeneity on welfare

To measure the effect of preference heterogeneity on the sum of landowner payoffs and the relative social cost of the externality, we compare the results in Tables 2 and 3 (preference homogeneity) with those in Table 4 (preference heterogeneity case). We report the comparisons for the cases where the bioinvasion starts on the forestland of the MES landowner and the case where it starts on the property of the NMES landowner.

The MES landowner's payoff decreases sizably in the presence of an NMES neighbor due to the under-provision of control on the NMES forestland. Furthermore, this decrease is larger when the NMES landowner is affected first by the bioinvasion. Compared to the preference homogeneity case, when the MES landowner has a neighbor with NMES preferences, and they are affected first by the bioinvasion, their payoff decreases from $12,491/acre (Table 3, preference homogeneity case) to $10,490/acre (Table 4, panel b), which amounts to approximately $2,000/acre, equivalent to a 16% decrease in payoff in the presence of preference heterogeneity. When the MES landowner is affected second by the bioinvasion, their payoff decreases by a larger amount, $4,886/acre (from $15,318/acre in Table 3 to $10,432/acre in Table 4, panel b), which is equivalent to a 32% decrease in payoff in the presence of preference heterogeneity.

In contrast, the NMES landowner's payoff is not meaningfully affected by the preferences of their neighbor. Compared to the preference homogeneity case, when the NMES landowner has a neighbor with MES preferences, and they are affected first by the bioinvasion, their payoff is negligibly lower: it decreases from $841/acre (Table 2, preference homogeneity case) to $831/acre (Table 4, panel c), which amounts to approximately $10/acre, equivalent to a 1% decrease in payoff in the presence of preference heterogeneity. Similarly, when the NMES landowner is affected second by the bioinvasion, their payoff decreases by 1% ($22/acre) in the presence of preference heterogeneity. (It decreases from 1,591/acre in Table 2, preference homogeneity case, to $1,569/acre in Table 3, panel c.)

Results in this section suggest that a transition from a landscape with homogeneous preferences to one with preference heterogeneity under the baseline parameter values is detrimental for the MES landowner but has no meaningful effect on the NMES landowner. If forest parcelization increases as a result of a demographic transition of landowners, results from the preference heterogeneity case, when compared with results from the preference homogeneity case, give insights as to how possible transitions might contribute to the production of bioinvasion externalities. We observe that when we move from NMES only to NMES and MES preferences co-existing on a connected landscape, the difference between DM and CP payoffs decreases from 48% (Table 2) to 30-40% (Table 4). In contrast, the CP-DM payoff difference increases from 11% (Table 3) to 30-40% (Table 4) when we move from MES only to co-existing NMES and MES preferences. That is, an increasing number of NMES-type parcels on a landscape dominated by MES-type ownerships increases the total economic damages from invasive species when NMES landowners act as weaker links in the landscape-level provision of bioinvasion control, regardless of where the bioinvasion starts.

Non-uniform subsidies for non-uniform preferences?

The social cost of the externality generated by the privately optimal decision of landowners can be reduced through a subsidy. Forest landowners in the U.S. have had access to technical and financial assistance to manage invasive species through many programs, notably the Environmental Quality Incentives Program (EQIP). A common feature among these programs is that the cost-share payments they provide are uniform in the sense that they are available to landowners regardless of landowner preferences or ownership motivations.

Taking the baseline model case of no subsidy (i.e., $c_{A,}$=c_B=\$4/ pine tree) as a baseline, we consider both uniform, e.g., (c_A, c_B) = (2,2), and non-uniform, e.g., (c_A, c_B) = (2,4) subsidies, under the cases where the bioinvasion starts on the NMES (G_A) and the MES (G_B) forestlands. Considering non-uniform subsidies is particularly interesting given the results on the previous section: If there is a landowner type that would control without the subsidy (i.e., the MES landowner), then non-uniform subsidies based on preferences and bioinvasion order might generate higher net aggregate payoff compared to uniform subsidies. Also, targeting the weaker-link landowners might increase the subsidy's cost-effectiveness by making control optimal for them and indirectly increasing returns to control for their neighbors through the complementarity of bioinvasion control on adjacent forestlands (Cornes 1993; Fenichel, Richards, and Shanafelt 2014; Atallah et al. 2017; Atallah et al. 2023). However, it might also be that targeting the forestland where the bioinvasion starts is more cost-effective, regardless of whether they are the weaker-link landowner.

Per acre cost-share pay rates range from 40% of the average cost of a practice and cannot exceed 75% of the documented cost (USDA NRCS 2011). In this model, such rates would be equivalent to per-tree costs of (c_A, c_B) = (2,2) and (c_A, c_B) = (1,1). That is subsidies of (2,2) and (3,3), respectively. We consider these subsidy schemes in addition to all possible combinations of non-uniform schemes and compare them to the baseline case of no subsidy.

Regardless of the move order, we find that a non-uniform subsidy of (3, 0), i.e., $3/treatment for *A* and no subsidy for *B*, maximizes the net aggregate payoff, defined as the aggregate payoff minus the total subsidy. In the case where the bioinvasion starts on G_A and *A* moves first, this non-uniform subsidy increases the net aggregate payoff by 56% relative to the baseline case of no subsidy. Uniform subsidies (2, 2) and (3,3) increase the net aggregate payoff by 51% and 45%, respectively, compared to the baseline of no subsidy (Table 5, panel a).

[Insert Table 5 here]

In the case where the bioinvasion starts on G_B and *B* moves first, a subsidy of (3, 0) increases the net aggregate payoff by 21% relative to the baseline case of no subsidy while uniform subsidies (3,3) and (2, 2) generate increases of 18 and 16%, respectively (Table 5, panel b). The relative increase in the net payoff is lower when Landowner *B* moves first in part because the baseline payoff is higher in that case ($12,060/acre; Table 5, panel b vs. $11,263/acre; Table 5, panel a) and because they control the bioinvasion early on and provide a benefit to landowner *A* as a result. Conversely, the relative increase in the net payoff is larger when *A* moves first because *A* does not control the bioinvasion in the baseline case.

The results in this section suggest that the subsidy scheme that maximizes the net aggregate payoff is a non-uniform subsidy consisting of no payment for the MES landowner and a 75% cost share for the NMES landowner, regardless of where the bioinvasion starts. Such non-uniform subsidy makes it privately optimal for the NMES landowner to control the bioinvasion. More interestingly, despite its being targeted to the NMES landowner, it indirectly incentivizes the MES landowner to initiate control earlier (Fig. 3a, panel 2 vs. panel 1) or to keep controlling later (Fig. 3b, panel 2 vs. panel 1), compared to the no subsidy case. As a result, the optimal subsidy leads to less intense and more frequent control, which is characteristic of a central planner's control program (Fig. 3, panel 2 vs. panel 3) or that of a landowner who equally values NMES and MES.

Sensitivity analyses

The results presented so far are relevant to a specific invasive shrub and one major type of NMES, namely, recreation. To test model robustness and expand its results to other invasive shrubs and types of NMES, we conduct four sets of sensitivity analyses. First, we conduct sensitivity analyses to the short and long-distance dispersal parameters to test the robustness of the model results to significant variations in these parameters and generate results that are illustrative of other invasive species that are more trivial or more catastrophic than glossy buckthorn. Second, we conduct sensitivity analyses to the recreation benefit parameters. Third, we consider the case where, in addition to trail recreation, the NMES landowner owns their forest for NMES benefits such as carbon sequestration, air purification, and water filtration, among others. Fourth, we consider the effect of surveillance and early detection on management.

Sensitivity to the short and long-distance dispersal parameters

We identify the threshold values for the parameters being varied that trigger a change in the control decisions of the landowners relative to the baseline results (Table 4b). In other words, for all values between the baseline value (Table 1) and the threshold value for each parameter (Table A1), there is no change in whether landowners control the bioinvasion relative to the baseline results.

Scenarios S1-4 in consist of univariate (i.e., one-way) sensitivity analyses, relative to the baseline scenario (S0): S1-2 represent the case with the slower and faster short-distance dispersal thresholds, respectively. S3-4 consider the case with the slower and faster long-distance dispersal thresholds, respectively. Scenarios S5-8 consist of bivariate (i.e., two-way) sensitivity analyses that represent a case where both dispersal mechanisms are slower (S5), a case where the short-distance dispersal is slower but the long-distance dispersal is faster (S6), a case where the short-distance dispersal is faster but the long-distance dispersal is slower (S7), and a case where both dispersal mechanisms are faster (S8) (Table A1).

In general, we find that the model results are robust to large changes in the dispersal parameter values. We identify thresholds parameter values beyond which the baseline results change to an outcome where either no bioinvasion control takes place on any forestland or an outcome where both landowners control the bioinvasion. These threshold values that qualitatively change the results are extreme in the case of the short-distance dispersal: The slower (α_{slower}=0.01 year^{-1}) and faster (α_{faster}= 3.91 year^{-1}) short-distance dispersal parameter threshold values correspond to environmental conditions or species where the probability of seed germination and establishment (conditional on one neighboring tree being infested) is 1% and 98%, respectively. (In the baseline case, this probability is 50% when α_{base}=0.69 year $^{-1}$.) In the case of the slower long-distance dispersal, the threshold parameter value that changes the optimal solution (γ_{slower}= 5) makes dispersal decay more rapidly over space so that long-distance arrivals reach only 19% of the neighboring forestland over 25 years (or three of the sixteen grid columns). In the case of the faster long-distance dispersal, the parameter threshold value (γ_{faster}= 1.5) makes dispersal decay over space so minimal that long-distance arrivals occur everywhere in the neighboring forestland. That is, the probability that a shrub on the westernmost border of one forestland causes an infestation on the easternmost border of the other forestland is greater than zero. [vii] The long-distance dispersal threshold parameters seem plausible relative to the extreme short-distance dispersal parameters. Slower and faster long-distance dispersal, or conversely, more or less rapid decay over space, represent the cases of invasive species that are spread by vectors that travel shorter (e.g., mammals) or farther (e.g., birds) distances. Results from these simulations can also illustrate the benefits of policies that seek to reduce short vs. long-distance dispersal directly.

The results in Table A1 suggest that, for a fast-enough long-distance dispersal (S4, S6, S8), none of the forest landowners control the bioinvasion, even if the short-distance dispersal is extremely slow (S6). In contrast, both landowners control the bioinvasion when either both dispersal mechanisms are at their low threshold (S5), or where one is at the low threshold, and the other is at the baseline value (S1, S3). The largest decrease in DM payoffs relative to CP payoffs (85%) occurs whenever the long-distance dispersal is at its faster threshold (γ_{faster}=1.5

in S4, S6, S8). In contrast, the difference between DM and CP payoffs is negligible (1%) when either the long-distance dispersal or both types of dispersal are at their slower thresholds (S3 and S5) (Table A1). The DM-CP difference is intermediary (14% in S1, 21% in S7, and 49% in S2) whenever the long-distance dispersal is at its baseline value or slower, regardless of the speed of the short-distance dispersal. Generally, these results show that whether an invasive plant causes a trivial problem (i.e., one that is resolved by control on both forestlands) or a severe one (i.e., where no landowner controls the bioinvasion) depends disproportionately on the long-distance dispersal. Given the large effects of moderate reductions in the long-distance, relative to the moderate effects of extreme reductions in the short-distance dispersal, it is surprising that there are few management actions, bioinvasion policies, or incentive programs that directly address the long-distance dispersal by birds, similar to policies that reduce human-mediated long-distance dispersal.[viii] Trakhtenbrot et al. (2005) suggest that this lack of appreciation of the significance of the long vs. short-distance dispersal in conservation policy and management is due in part to difficulties in definition and quantification of long-distance dispersal. There are conservation policy recommendations that seek to affect long-distance bird-mediated dispersal when it is desirable but insufficient: for example, Amezaga et al. (2002) suggest considering the migration routes of waterfowl that vector aquatic invertebrates when constructing wetland reserve networks. But we do not know of policies that are designed to reduce undesirable long-distance dispersal of invasive plant seeds by birds. The sensitivity of the model results to the long-distance dispersal parameter suggests that there might be economic benefits to investing in long-distance bird dispersal research that can inform bioinvasion management and policy.
Management strategies and policies focused on reducing the source of the bioinvasion alone

through shrub removal, holding dispersal constant, might have limited success in reducing externalities relative to slowing down dispersal, especially the long-distance kind.

The sensitivity results presented here can also be interpreted as showing that the baseline results extend to other invasive shrubs with slower and faster, short, and long-distance dispersal that falls between the baseline and threshold values. The results at and beyond the threshold values illustrate how the model can be adapted for other invasive species with extremely slow and fast short-distance dispersal (S1 and S2), negligible slow long-distance dispersal (S3), and relatively fast long-distance dispersal (S4).

Sensitivity to the recreation benefit parameters

In the baseline case, we considered that the NMES landowner derives trail recreation benefits from healthy trees. Here, we conduct sensitivity analyses to the parameters of the recreation benefit parameters (b_0, a_1 and b_1 in the user day, UD, and consumer surplus, CS, functions; Eq. 1 and Table 1). We identify threshold parameter values beyond which the optimal solution changes such that both landowners control the bioinvasion, and the difference between DM and CP payoffs is decreased. The intercept of the user days function (b_0 in Table 1) represents the number of days an NMES landowner recreates on their forestland with no healthy trees. We find that, for values of b_0 equal to or greater than 28 days per year, up from 9 days/year in the baseline case, the NMES landowner controls the bioinvasion. At this threshold parameter value, the CP-DM payoff difference is reduced to 11%, compared to 40% in the baseline case (Table A2-a; Appendix A). We also find that if parameter a_1 is equal to or greater than \$0.36 per user day for each additional healthy tree per acre, and parameter b_1 is equal to or greater than 0.36 days per additional healthy tree per acre, the NMES landowner controls the bioinvasion. At these threshold values, the difference between DM and CP payoffs is 9%, down from 40% in the baseline case (Table A2-b). These results illustrate how the baseline results might change for NMES landowners who derive higher trail recreation values from their trees.

Beyond recreation benefits

In this section, we expand the bundle of NMES benefits and consider that, in addition to trail recreation, the NMES landowner derives benefits from ES such as carbon sequestration, pollutant removal from the air, and water filtration. We add a term in the NMES discounted benefit function that increases in the number of healthy and infested trees, excluding only those that are heavily infested. In this term, we make two modifications to accommodate these types of NMES. First, we relax the spatial contiguity constraint in Eq. 3 that is not relevant for NMES whose provision and damage are not spatially defined (i.e., tree location on or away from a trail does not matter for carbon sequestration or air purification). Second, we include trees invaded at the *Low* and *Moderate* levels considering that, while the shrub invasion at these levels affects aesthetics and hiking recreation benefits, it does not affect a tree's ability to store carbon or remove fine particles from the air. We identify threshold parameter values beyond which the NMES landowner controls the bioinvasion. We find that this outcome occurs when the NMES landowner derives yearly benefits from NMES, such as carbon sequestration, air purification, and water filtration that are equal to or greater than $350 per acre (or $0.45/tree). For example, if the NMES landowner considers carbon sequestration benefits in their private bioinvasion control decision making, then the threshold value we identify here tells us how large this privately-held value needs to be for the landowner to initiate bioinvasion control. At this threshold value, the difference between DM and CP payoffs is 3%, down from 40% in the baseline case (Table A2-

c). In comparison, existing estimates of stated forest landowner carbon sequestration benefits range from 5 to 30 $/acre/year (Fletcher, Kittredge, and Stevens 2009; White et al. 2018).

Surveillance, early detection, and management.

In the baseline model, the landowners only observe the bioinvasion states *Invaded-moderate* (I_m) and *Invaded-high* (I_h), at which point 19% of the trees are *Invaded-undetectable* (*Iu*) or *Invaded-detectable (Id)*, 13% are moderately infested, and none are heavily infested. However, extension services or Cooperative Invasive Species Management Areas provide technical assistance and training in identification, and monitoring (Ingle 2013; Cronk 2017), which can give landowners the ability to detect the bioinvasion at the *Invaded-detectable* (I_u) state, before shrubs produce berries and form clumps. We consider that, even with surveillance, landowners do not observe the invasive shrub when it is still at the seed germination stage (*Invaded-undetectable*).

We find that, when surveillance is possible under the baseline model parameters, the NMES landowner still does not find it optimal to control the bioinvasion even if the invasive shrub is discoverable earlier. The MES landowner, in contrast, starts controlling five years earlier because of surveillance and early detection and decreases the total number of treatments by 8% (the difference between 1,548 treatments in Table 4b and 1,416 treatments in Table A3-a; Appendix A). The possibility of surveillance and early detection benefits both landowners, even if only one of them engages in it. The benefits of earlier and less intense treatment by the MES landowner increase the payoffs of the NMES landowner by 98% (the difference between $831 in Table 4b and $1,648 in Table A3-a). The aggregate benefit of surveillance and early detection is $1,635/two acres, an increase of 15% relative to the baseline.

We also consider a case where the short-distance dispersal is at its lower threshold (Table A1-S1; Appendix A). We find that, if short-distance dispersal is slow, surveillance and early detection are available, and the invasive shrub is instantly detectable (i.e., L_1 =0), both landowners find it optimal to engage in earlier control and to conduct 9% fewer treatments in total, relative to the slow short-distance dispersal baseline (1,520 vs. 1,866 treatments in total, 654 vs. 868 treatments for the NMES landowner and 866 vs. 997 for the MES landowner; Table A1-S1 vs. Table A3-b; Appendix A). The benefits of earlier and less intense treatment consist of a 25% increase in the payoffs of the NMES landowner and a 6% increase in the payoffs of the MES landowner. (The percentage increases are the difference between $2,319 in Table A3-b and $1,859 in Table A1-S1 in the case of the NMES landowner and the difference between $16,261 in Table A3-b and $15,287 in Table A1-S1 in the case of the MES landowner, respectively). These results illustrate the benefits of early detection training on reducing the costs and damages generated by the invasive shrub. Expectedly, reductions are larger for faster-spreading invasive species (33% vs. 13%; Table A3-b).

Conclusions

In this article, we proposed a two-agent model of bioinvasion control where preferences can be heterogeneous, and strategic bioinvasion control is affected by the spatial externality that links agent payoffs. Our model results suggest that both the initial incidence of a bioinvasion and landowner preference heterogeneity are drivers for the generation of bioinvasion externalities and the relative magnitude of the social cost they generate. However, whether heterogeneity exacerbates or mitigates externalities depends on the preference-type of landowners: NMES landowners act as a weaker link in the provision of bioinvasion control and exacerbate the externalities for MES landowners. In contrast, MES landowners generate benefits to NMES landowners, especially when they are first affected by a bioinvasion and move first. These results provide preliminary insights on how possible further parcelization of forest landownership might affect bioinvasions and their private control. The insights gained from the model results could not have been obtained by a model that assumes preference homogeneity or does not account for the co-dependence of agent payoffs through the spatial externalities. Specifically, the ES damages for the NMES landowner would have been underestimated if ES values were assumed to be spatially uniform. The use of cellular automata allowed the modeling of spatially-explicit ES production and damage functions that would not have been possible to represent in a non-spatial model or in a spatial model where space is only defined at the property boundaries.

Subsidies address the under-provision of bioinvasion control, but the cost-effectiveness of uniform subsidy schemes consistent with those currently in place (e.g., EQIP) can be improved upon. The subsidy scheme that is most cost-effective is non-uniform, consisting of a 75% cost share for the weaker link NMES landowner who would not control otherwise and no cost share for the MES landowner for whom it is privately optimal to control, regardless of where the bioinvasion starts. While it might not always be possible to observe the preferences of households when devising non-uniform instruments, an assumption that underlies the result of decentralized management being preferred to centralized management in the presence of preference heterogeneity (Costello and Kaffine 2017), it is possible to distinguish between MES and NMES-type landowners based on timber income reports.

Model results depend disproportionately on changes in the long-distance dispersal, relative to the changes in the short-distance dispersal of the invasive species. Our results support future research on bioinvasion policies that address long-distance dispersal directly. Because of its ability to characterize both short and long-distance dispersal, this model is generalizable to other invasive species that have faster or slower short and long-distance dispersal mechanisms.

Examples of interesting applications include Kudzu (*Pueraria montana*), which has a fast short-distance dispersal, and purple loosestrife (*Lythrum salicaria*) that has a fast long-distance dispersal. Norway maple (*Acer pseudoplatanaus*) and Amur honeysuckle (*Lonicera maackii*) are examples of invasive forest shrubs with relatively slow short distance dispersal mechanisms. Similarly, because of its ability to include both MES and NMES benefits, this model can be extended to include a third landowner type whose preferences include varying relative weights on MES and NMES benefits. The model may also be extended to include public lands as an additional landownership type with multiple uses, which is relevant for the Western U.S. where private lands are often adjacent to public lands.

This study has focused on the noncooperative case with information sharing. However, there is scope for cooperative solutions: MES landowners participating in Cooperative Invasive Species Management Areas might create a fund that can be used to transfer payments to NMES landowners to subsidize their bioinvasion control. These funds and the grants that channel them can serve as the vehicle for the subsidies studied in this paper to generate outcomes close to the central planner's.

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TABLES

Table 1. Model Parameters.

Parameter	Description	Value	Unit
Objective function parameters			
a_0	Intercept of the consumer surplus (CS) function	-2.97 [a]	\$/day
b_0	Intercept of the user days (UD) function	9.32 [a]	Days/year
a_1	Linear parameter of the CS function	0.24 [a]	\$/day/healthy tree
b_1	Linear parameter of the UD function	0.24 [a]	Days/healthy tree
a_2	Quadratic parameter of CS function	-0.00017 [a];	Unitless
b_2	Quadratic parameter of UD function	- 0.0002 [a]	Unitless
p	Timber prices for *Young* and *Mature* trees	0.11, 0.13 [b]	\$/board feet (BF)
$y_{m,n,t}$	Timber yields for *Mature* trees	297 [c]	BF/tree
c_A, c_B	Bioinvasion treatment cost	4 [d]	\$/ invaded tree
ρ	Discount factor	0.961538	year $^{-1}$
T	Forward-looking years (over five stages)	5, 10,…, 25 [e]	years
Spatial-dynamic externality parameters			
α	Short distance H to E_u transition rate	0.69	year^{-1}
$N_{i,j,t}$	Number of contiguous I_m or $I_h$neighbors	0,…,8	cells
γ	Long distance power-law parameter	3	unitless
L_1	Average waiting time between *Invaded-undetectable* and *Invaded-detectable* [f]	1	year
L_2	Average waiting time between *Invaded-detectable* to *Invaded-moderate* [g]	1	year
L_3	Average waiting time between *Invaded-moderate* to *Invaded-high* [h]	2	years
τ_{young}	Years between *Juvenile* and *Young* if tree and its immediate neighbors are *Healthy*.	10	years
τ_{mature}	Years between *Young* and *Mature.*	10	years
$I * J$	Grid G_A dimensions	49*16=784	rows x columns
$M * N$	Grid G_B dimensions	49*16=784	(trees per acre)

[a] Values from Rosenberger et al. (2013), adjusting for tree density per acre in the case of a_1 and b_1; [b] NHDRA (2016); [c] Hepp et al. (2015) and Smalley et al. (2016); [d] Ending the analysis at 25 years is consistent with landowner demographics and plans (most private forest landowners are above 65 years old and plan to sell or transfer their land; USFS 2015); [e] Lee (2017); assumes repeated cutting in the spring, summer, and fall to avoid re-growth. [f] $\alpha_2 = \Pr\left(s_{i,j,t+1} = I_d \middle| s_{i,j,t} = I_u\right) = 1 - e^{-1/L_1}$; [g] $\alpha_3 = \Pr\left(s_{i,j,t+1} = I_m \middle| s_{i,j,t} = I_d\right) = 1 - e^{-1/L_2}$; [h] $\alpha_4 = \Pr\left(s_{i,j,t+1} = I_h \middle| s_{i,j,t} = I_m\right) = 1 - e^{-1/L_3}$

Table 2. Landowners' Payoffs ($/acre) and Optimal Amount of Control Under Decentralized Management (DM) and Central Planner (CP) Cases; homogeneous preferences case where both landowners have non-market ecosystem service (NMES) preferences.

	DM		CP		Social cost of externality	
	Payoffs	Control	Payoff	Control	DM w.r.t. CP	
	$/acre	*Treatments*	*$/two acres*	*Treatments*	*$/two acres*	*%*
First mover	841 (77)	0	2,203 (82)	783 (28)	n/a	n/a
Second mover	1,591 (123)	0	2,509 (64)	682 (25)	n/a	n/a
Sum	2,432 (145)	0	4,712 (104)	1,465 (38)	- 2,280***	- 48

n/a: not applicable; w.r.t.: with respect to; *** Statistically different from zero at the 1% level. Standard deviations in parentheses.

Table 3. Landowners' Payoffs ($/acre) and Optimal Amount of Control Under Decentralized Management (DM) and Central Planner (CP) Cases; homogeneous preferences case where both landowners have market ecosystem service (MES) preferences.

	DM		CP		Social cost of externality	
	Payoffs	Control	Payoff	Control	DM w.r.t. CP	
	$/acre	*Treatments*	*$/two acres*	*Treatments*	*$/two acres*	*%*
First mover	12,491 (2,885)	1,203 (12)	15,467 (3,346)	944 (33)	n/a	n/a
Second mover	15,318 (3,114)	962 (13)	15,847 (3,318)	744 (28)	n/a	n/a
Sum	27,808 (4,245)	2,165 (18)	31,314 (4,712)	1,688 (43)	- 3,506***	-11

n/a: not applicable; w.r.t.: with respect to. *** Statistically different from zero at the 1% level.

Standard deviations in parentheses.

Table 4. Landowners' Payoffs ($) and Optimal Amount of Control (treatments) Under Decentralized Management (DM) and Central Planner (CP) Cases for Landowner *A* (non-market ecosystem service preferences, NMES) and Landowner *B* (market ecosystem service preferences, MES).

a. G_A and G_B are ecologically isolated (no long-distance dispersal, LDD2)

	DM		CP		Social cost of externality	
	Payoffs	Control	Payoff	Control	DM w.r.t. CP	
	$/acre	*Treatments*	*$/two acres*	*Treatments*	*$/two acres*	*%*
G_A (NMES)	2,999 (42)	498 (7)	n/a	498 (7)	n/a	n/a
G_B (MES)	16,731 (3,384)	497 (9)	n/a	497 (9)	n/a	n/a
G_A+G_B	19,731 (3,384)	995 (11)	19,731 (3,384)	995 (11)	0	0

b. Bioinvasion starts on G_A and A (NMES) moves first

	DM		CP		Social cost of externality	
	Payoffs	Control	Payoff	Control	DM w.r.t. CP	
	$/acre	*Treatments*	*$/two acres*	*Treatments*	*$/two acres*	*%*
G_A (NMES)	831 (73)	0 (0)	2,187 (152)	836 (32)	n/a	n/a
G_B (MES)	10,432 (2,453)	1,543 (12)	16,667(3,367)	700 (29)	n/a	n/a
G_A+G_B	11,263 (2,453)	1,543 (12)	18,854 (3,370)	1,536 (43)	- 7,591***	- 40

c. Bioinvasion starts on G_B and B (MES) moves first

	DM		CP		Social cost of externality	
	Payoffs	Control	Payoff	Control	DM w.r.t. CP	
	$/acre	*Treatments*	*$/two acres*	*Treatments*	*$/two acres*	*%*
G_A (NMES)	1,569 (123)	0 (0)	2,119 (72)	812 (26)	n/a	n/a
G_B (MES)	10,490 (2,121)	785 (0)	15,127(3,357)	1,025 (33)	n/a	n/a
G_A+G_B	12,060 (2,125)	785 (0)	17,246 (3,358)	1,837 (42)	- 5,187***	- 30

n/a: not applicable; w.r.t.: with respect to; *** Statistically different from zero at the 1% level.

Standard deviations in parentheses.

Table 5. **Net Aggregate Payoffs for Different Levels of Uniform and Non-uniform Subsidies for Landowner *A* (non-market ecosystem service preferences, NMES) and Landowner *B* (market ecosystem service preferences, MES).**

Cost (c_A, c_B)	Subsidy (p_A, p_B)	Control in G_A	Control in G_B	Aggregate control	Aggregate payoffs	Total subsidy cost [a]	Net aggregate payoffs [a, b]	Change relative to baseline
$/ treatment			*Treatments*			*$/two acres*		
(a) Bioinvasion starts on G_A and *A* (NMES) moves first								
(4,4)	(0,0)	0	1,543	1,543	11,263	0	11,263	0%
(1,1)	(3,3)	1,358	1,180	2,537	20,992	4,653	16,339	45%
(2,2)	(2,2)	1,041	865	1,905	19,547	2,532	17,015	51%
(1,4)	(3,0)	1,042	603	1,644	19,546	2,016	17,529	56%
(b) Bioinvasion starts on G_B and *B* (MES) moves first								
(4,4)	(0,0)	0	785	785	12,060	0	12,060	0%
(2,2)	(2,2)	1,390	1,649	3,038	17,751	3,765	13,986	16%
(1,1)	(3,3)	1,225	1,673	2,898	19,802	5,562	14,240	18%
(1,4)	(3,0)	1,480	1,207	2,686	17,547	2,921	14,626	21%

[a] In present value terms (25 years, 4% annual discount rate)

[b] Defined as aggregate payoffs minus total subsidy; standard deviations not reported.

FIGURE TITLES

Figure 1. Short-distance dispersal (SDD) and long-distance dispersal (LDD1 and LDD2) Shaded cells represent invaded cells on the grid. Lightning bolts represent random long-distance dispersal events that are exogenous to the model (LDD1).

Figure 2. Optimal bioinvasion control in forestlands GA and GB where they both have market ecosystem service (MES) preferences.

(a) Bioinvasion starts on G_A *and A moves first*

(b) Bioinvasion starts on G_B *and B moves first*

Figure 3. Optimal bioinvasion control where landowner *A* has non-market ecosystem service (NMES) preferences and landowner *B* has market ecosystem service (MES) preferences.

(a) Bioinvasion starts on G_A *and A moves first*

(b) Bioinvasion starts on G_B *and B moves first*

1. No subsidy

2. Optimal subsidy

3. Central planner

FOOTNOTES

[i] See Urquhart and Courtney (2011) for comparable ownership motivations in the United Kingdom.

[ii] Parcelization, defined as the subdivision of tracts into smaller ownerships, can occur when the land is divided among heirs and when part or all of the land is sold to pay estate and inheritance taxes (Mehmood and Zhang 2001).

[iii] Jardine and Sanchirico (2018) provide empirical evidence that the invasive plant control cost function is linear in removal.

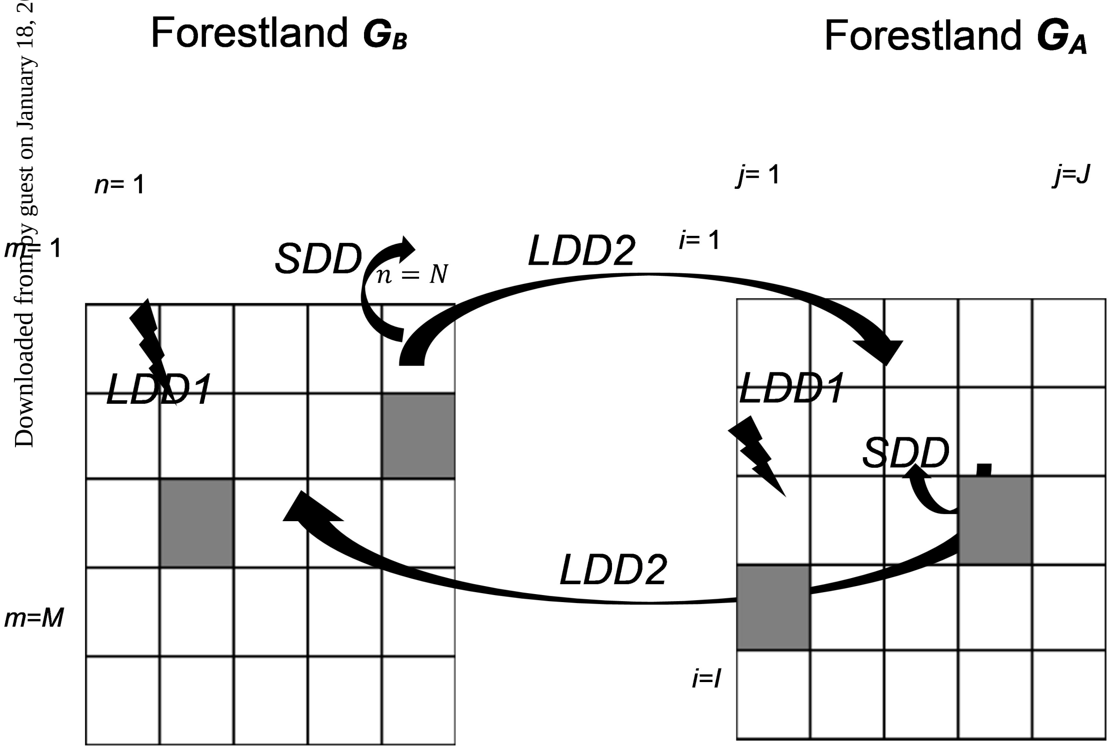
[iv] For problem formulation in the case of an industrial forest manger making bioinvasion decisions over an infinite horizon, see Macpherson et al. (2018): whether the optimal harvest (which is also the disease control strategy in their case, i.e., tree removal) is affected as a result of a forest disease depends on the rate of infection and on the extent of disease timber damage. They find that when the value from infected timber is non-zero and an infection spreads quickly, it can be optimal to harvest at the disease-free optimal rotation length to harvest.

[v] Given the two-agent nature of this model, and our interest in estimating the social cost of the externality imposed by one landowner on the other, the CP payoff does not include the value of trees outside of the benefits to landowners *A* and *B*. For applications that account for the values of trees to society at large such as health benefits, see Jones, McDermott and Chermak (2016).

[vi] These values represent 31 and 27 shrub removals through stem cutting per year, which represents controlling 4% and 3% of the pine trees each year by having the shrub removed from underneath them, respectively.

[vii] The long-distance dispersal is faster when the exponent γ on column j (i.e., distance) (Eq. 8a) is smaller and probability α_1 (Eq. 6) declines less rapidly over distance.

[viii] The Nature Conservancy's *Don't Move Firewood* educational campaign, among other initiatives, is designed to reduce the long-distance dispersal of the emerald ash borer by humans.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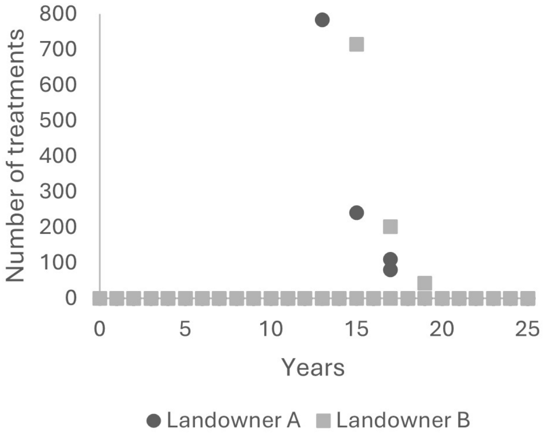
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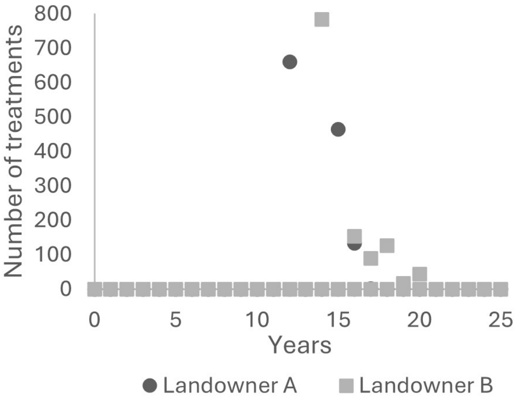
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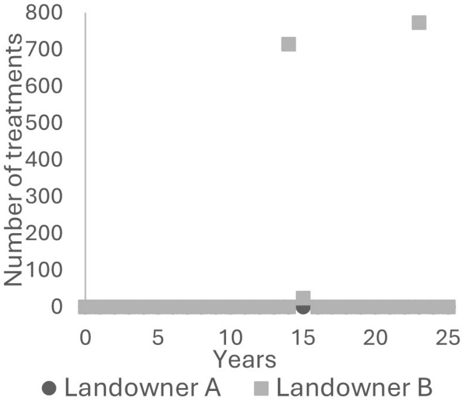
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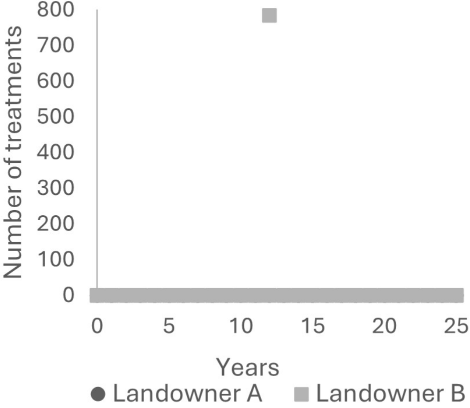

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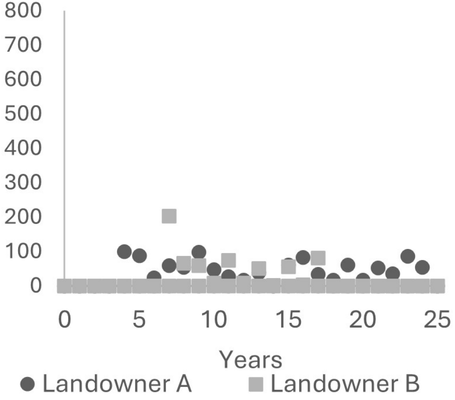
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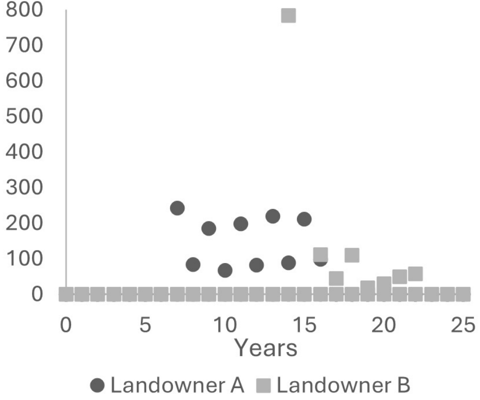

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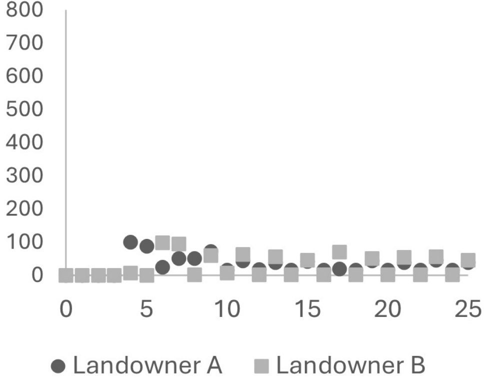
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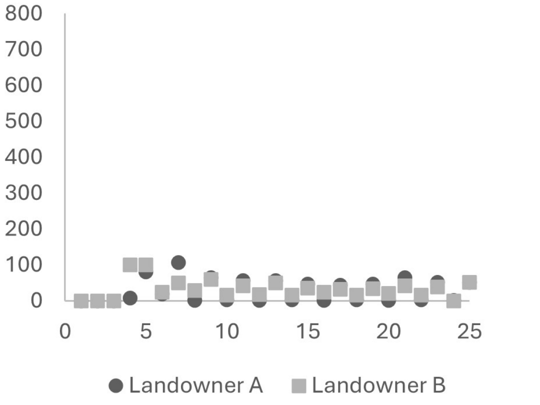
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