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Abstract

We consider optimal behavior in a class of spatial-dynamic economic problems related to a negative externality with stock effects, via the development of a dynamic, non-cooperative game. Feedback Nash equilibrium response functions are parameterized based on an invasive weed found on western US cattle ranches. Simulations illustrate trade-offs between increasing costs of management efforts, the invasives' impact on productivity and temporal growth impacts, when another agent's effort and infestation levels are considered. Symmetric and asymmetric cases as well as the socially optimal and second-best alternatives are considered. Optimal strategies are often case specific, exemplifying the complexity of management.

Key Words: renewable resources, externalities, dynamic games, invasive species, simulation

1.0 Introduction

Invasive species negatively impact local and regional economies through increased cropping, grazing, and recreational costs, as well as through impacts on water quality and quantity and soil quality. Specific to invasive weeds one often cited study (Pimentel *et al.* 2005) estimates that invasive weeds cost US agriculture about $24 billion annually. There is little doubt that size of these damages, particularly in individual agricultural sectors, inflict substantial costs on the industry and that the control of invasive weeds could produce significant benefits.

Efficiently controlling invasive species, however, is a complex management problem for many reasons. For example, the speed with which the problem is recognized and control decisions are made can greatly impact the level of harm caused by the invasion and mitigation costs. In addition, those impacted (even if they undertake mitigation) have the economic incentive to base their decisions on private benefits and costs, which can lead to a less than efficient control level. From the public perspective, providing the individual incentives to efficiently control invasions is impossible without understanding the behavioral characteristics of the private parties and the interdependencies in their private decisions. These problem characteristics are not unique to invasive species and can be found in other spatial-dynamic problems related to natural resources (see, Smith *et al.* 2009, for a review). While possible complexities in the evolution of biological agents have been scrutinized in economic frameworks, the possibility for strategic behavior by economic agents in spatial-dynamic problems has been largely ignored, although there is a substantial literature on strategic behavior applied to other environmental problems (e.g., Puller 2006). Specific to cattle ranching, a recent survey by Thacher *et al.* (2009) suggests ranchers do consider strategy. For example, a majority of respondents indicate they would increase their weed management effort if their neighbors increased their effort. Is this an optimal strategy? If yes, then under what conditions? If no, what is an optimal strategy?

In order to help answer such questions, we construct a dynamic, non-cooperative game to provide insight into agents' optimal actions when the individual agent faces an invasive weed on his rangeland. The growth of the invasive on an agent's rangeland is impacted not only by the state of his land and his actions, but also by that of other agents. If agents recognize the impact of others on their production, they naturally take this into account in their decisions. We assume this to be the case and account for these interactions in decisions and states with a feedback Nash-solution-path of effort for the individual agent. This allows insight into the impact from the growth of the invasive as well as from the actions of other agents.

Utilizing this model we perform a series of dynamic numerical simulations, stylized for Yellow Starthistle (YST) and beef cattle ranching in semi-arid western states where YST is present, but has not yet resulted in substantial economic impacts (e.g., New Mexico, Colorado, or Arizona). We find that at low-level infestations (10%), initial optimal efforts are high, eradicating 90% of the invasive that is present in the initial time period. At the highest initial level of the infestation simulated (50%), optimal effort in the initial period eradicates less than 80% of the invasive. These results are consistent with those of Olson and Roy (2008) in a more general setting.

With asymmetric agents, the agent with the lower infestation finds it optimal, in some cases to exert more effort (relative to the symmetric case), thereby avoiding a large negative impact on his own net present value (NPV). Agents with higher initial infestations can enjoy positive externalities being adjacent to lower level infestation agents. Furthermore, if the high infestation level (50%) agent initially does nothing, their second-best path is to continue to do nothing. When faced with this agent, the low-level infestation agent finds it optimal to exert maximum effort in every period. These results, while stylized, suggest that the effective management of a negative externality, invasive species will require a superior understanding of the biologic spread of the species and the strategic economic choices of individual agents. Efficient management efforts may be scenario specific.

2.0 Background

When characterizing equilibria in strategic-form, non-cooperative games, Nash's (1951) approach has been referred to as "probably the most important solution concept in game theory" (Meyerson, 1991, p.105). The key element of the Nash equilibrium in this setting is that no player can increase his payoff by unilaterally deviating from the strategy profile, making it self-enforcing. This powerful condition holds whether players select pure or mixed strategies and allows us to conveniently consider the case of asymmetric agents.

Martin *et al*. (1993) developed one of the first dynamic games, applied to a transboundary pollution stock with asymmetric agents. They employed subgame perfect, feedback Nash equilbria. This allows for players' optimal strategy sets to define an equilibrium set of decisions at any point in time. The model for a single pollutant stock provides a policy evaluation for tax/subsidy schemes for the transboundary pollutant. Other single stock games include Mäler and De Zeeuw (1998), who constructed an acid rain differential game focusing on individual agents' buffer stocks, which include non-cooperative feedback Nash equilibria. Both models include a diffusion factor. Specific to wildlife, Clement and Wan (1985) develop a predator-prey, common pool game that allows for agents to harvest from either the predator or prey stock. Bhat and Huffaker (2007) develop a dynamic game for the management of transboundary, nuisance-wildlife populations and focus on variable-transfer-payments contracts. Specific to invasive weeds, Grimsrud *et al.* (2008) construct an open-loop Nash equilibrium game.

There is a growing literature modeling the interactions between grazing, stocking rates, and the level of invasives. For example, Finnoff *et al.* (2008) find that nitrogen deposition and stocking practices determine optimal cattle stocking rates when invasives are present; however they ignore possible strategic rancher behavior. Eiswerth and van Kooten (2007) attempt to deal with the complex issues in grazing-land economic damage and invasive's control using a model of learning. Their approach tends to beg the question of how long ranchers might be expected to continue learning before behaving strategically and reacting optimally to other's control efforts. In an earlier paper, Eiswerth and van Kooten (2002) developed a stochastic optimal control model for an invasive weed in California and provided an empirical illustration of the model results finding the optimal management choice and comparing the result to a mangemnt strategy of eradication. They find management, rather than eradication, is optimal.

Our research draws on key aspects of the above literature for the dynamic, strategic invasive weed problem. In the next section,we present the feedback Nash equilibrium theoretical model and its parameterization. Section four presents dynamic simulations based on the parameterized model with sub-sections for variations in carrying capacity, for asymmetric agents, social optimality including the value of information, and the second-best with a myopic starting point. Section five makes conclusions and considers some possible extensions.

3.0 Theoretic Model

Consider the case where the private agents are cattle ranchers who can run their cattle on their own private land or on public lands to which they hold permits. Let $\theta_i(t)$ define the stock of the invasive species (state variable) and $w_i(t)$ denote the management effort of agent *i* during time *t* (control variable). Let the game have *N* heterogeneous agents where agent *i*'s net benefits from management choices for a certain level of infestation are conditioned on a vector of characteristics specific to that individual, $\mathbf{A_i}$ (e.g., risk preferences or management style) or land characteristics (e.g., distribution and/or size of land parcels, or land ownership). In reality, the benefits are indirectly a function of the state, as the level of infestation impacts the forage, which in turn impacts the output of this process, which is the volume of beef available for market. We define benefits for agent *i* by[1];

$$B_i(w(t), \theta_i(t); \mathbf{A_i}),\ i = 1, ..., N,\ \ t = 1, ..., T. \tag{1}$$

We allow for asymmetries in net benefits associated with management effort. For some subset of the *N* agents, $(j = 1, ..., k)$, there are positive net benefits from management effort, that is, $\partial B_i / \partial w_i > 0$, while for the remaining agents $(k + 1, ..., N)$, there are negative net benefits associated with management, $\partial B_i / \partial w_i < 0$. In either case there are diminishing returns to invasive species management, $\partial^2 B_i / \partial w_i^2 < 0$. Furthermore, $\partial B_i / \partial \theta_i < 0$ and $\partial^2 B_i / \partial \theta_i^2 < 0$. That is, benefits are inversely related to and diminishing in the stock of the invasive species. The impact on benefits of each of the individual's characteristics depends on the individual observable characteristic in question. Let a_i represent a single characteristic of agent *i*, where $a_i \in \mathbf{A}_i$. Then $\partial B_i / \partial a_i \lesseqgtr 0$, depending on the characteristic in question.

Conditional on the initial state, $\theta_i(0) = \theta_{i,0}$, agent *i* will choose the management path over time that maximizes

$$J_i\left(\theta_{i,0};\left[w_i(t),\mathbf{w_j}(t)\right]_0^T\right)=\int_{t=0}^{T}e^{-r_it}\left[B_i(\theta_i(t),w_i(t);\mathbf{A_i})\right]dt \tag{2}$$

given the choices of other agents where $\mathbf{w_j}(t)$ is the vector of all other agents' $(i \notin \mathbf{j})$ management choices from $t = 0,...,T$. A terminal future period is chosen to mirror the fact that agents would be unlikely to consider the possible infinite future impacts of their actions. The assumption also makes extensions to consider the more likely impacts of shortening of time horizons, more straight-forward.

Similar to Eiswerth and Johnson (2002) we model the transition equation including the weed growth rate, $g_i(\theta_i(t))$. We also allow that the effort of all agents, $\mathbf{w}(t)$, and the effectiveness of the management effort of all agents, ψ can impact growth. That is[2];

$$\dot{\theta}_i(t)=f_i\left(g_i(\theta(t)),\mathbf{w}(t),\psi\right) \tag{3}$$

where $0 \le \psi \le 1$. Equation (3) defines the invasive species stock at any point in time.

Each agent *i*, at time *t*, observes the current level of stock and then chooses the optimal management effort consistent with $w_i(t)=\eta_i(\theta_i(t))$. This rule defines a mapping of management effort levels associated with each potential stock level, $\theta_i(t)$. A solution to this game is determined by the set of *N* strategies that result in an equilibrium. We assume all agents make their management effort choices simultaneously in each instant of the game. Further we assume each agent takes all other players' strategies into account in making his or her decision. A Nash equilibrium occurs if

$$J_i\left(\theta_{i,0};\left[\eta_i^*(\theta_i(t)),\eta_j^*(\theta_j(t))\right]_{t=0}^T\right)\ge J_i\left(\theta_{i,0};\left[\eta_i(\theta_i(t)),\eta_j^*(\theta_j(t))\right]_{t=0}^T\right), \tag{4}$$

where "*" indicates the optimal path, defined as the path of strategies through time that yields agent *i* cumulative net benefits at least as large or larger than any other path would, given the strategy choices of all other players. Thus agents affected by invasive species will determine their management strategy conditional on all other agents' management strategies with respect to the invasive species. The invasive species management problem is hence formulated as a negative externality problem where the impact of actions on the individual agent's stock is determined by collective decisions about management efforts and other agents' stocks, where the individual agent will not observe any effects of collective management choices on the stock of the invasive species until the next time period.[3]

At this level of generality we can say little concerning the characteristics of the optimal effort path for an individual agent. Thus, we turn to specific functional forms that provide an interior solution to the problem and allow us to focus on the economics of the dynamic game. [4]

Consider the price-taking, profit maximizing beef producer who is confronted with an invasive weed that impacts the productivity of his or her rangeland (where *N*=*i*,*j*). Agent *i*'s gross profits (*GP*) are described by;

$$GP_i = p\bar{S}_i(1-\theta_i),$$

where

p = per pound price of beef (net of costs to produce beef),
$\bar{S}_i$ = pounds of beef available for sale produced at maximum carrying capacity of beef per acre (assumed constant), and
θ_i = percentage of acres infested by invasive weeds, $0 \le \theta_i \le 1$.

We assume agent *i* produces at the optimal carrying capacity on the land, given the level of infestation. Thus, if there are no invasive weeds $(\theta_i = 0)$, production is that attainable at maximum carrying capacity, $\bar{S}_i$. As the level of the invasive increases, productivity of the land, $\bar{S}_i(1-\theta_i)$, decreases proportionately to the level of infestation. A complete infestation corresponds to a level of invasion where there may be some feed-grasses remaining on some of the acreage but at insufficient levels to sustain a minimal number of cattle without additional feed sources.[5]

Costs to eradicate or remove the invasive weeds in a single period (assumed additively separable from the costs to produce beef) are described by the quadratic form

$$TC_i = a_i \theta_i w_i + b_i w_i^2 \tag{5}$$

where w_i = agent i's effort to eradicate, where the weed percentage eradicated is $0 \leq w_i \leq \theta_i$ and a_i and b_i are positive constant parameters associated with removing w_i of an infestation. From this $\partial TC_i / \partial w_i > 0$, $\partial^2 TC_i / w_i^2 > 0$, $\partial TC_i / \partial \theta_i > 0$, and $\partial^2 TC_i / \partial \theta_i^2 = 0$, resulting in increasing marginal costs of effort and higher costs to remove with higher infestation levels.

We model the growth of the invasive species on agent i's as

$$\dot{\theta}_i(t) = \rho_i \theta_i(t) - w_i(t)\left(1 + \gamma_i w_j(t)\right) + \sigma_i \bar{S}_i \left(1 - \theta_i(t)\right) + \phi_i \left(\theta_j(t) - w_j(t)\right) + d_i. \tag{6}$$

Equation (6) allows the growth of the invasive weed to be dependent on a number of factors. First, the existing weed infestation on the land grows, $\rho_i \theta_i(t)$, where ρ_i is the intrinsic growth rate specific to agent i's land. We allow for impacts on growth by the actions of agents i and j. [6] Effort by agent i reduces the growth of the infestation. In addition, there can be synergies between agents' efforts. The impact of i's effort and the synergistic effort of i and j is represented by $\left[-w_i(t)\left(1 + \gamma_i w_j(t)\right)\right]$, where γ_i is a positive constant specific to agent i's problem and $w_i(t)$ and $w_j(t)$ are the effort levels of agents i and j, respectively in time t.

Grazing activity on agent i's land impacts the level of infestation. Grazing stresses the non-weed stock, while leaving the invasive untouched, allowing the invasive greater growth.[7]

The proportional increase in growth of weeds from grazing activity is described by $\left[\sigma_i \bar{S}_i(1-\theta_i(t))\right]$, where σ_i is a positive constant specific to agent *i*'s problem.

The level of the invasive can also be impacted by the state of other agents' lands (e.g., from wind or water transport) and their individual efforts, $\left[\phi_i\left(\theta_j(t)-w_j(t)\right)\right]$, where ϕ_i, a positive constant, is the dispersion factor from agent *j*'s land to agent *i*'s land. Finally, the level of infestation can be impacted by dispersion not associated with other agents, d_i. This is a positive constant, which could, for example, represent transport by tires or animals from community activities.

Assuming a fixed time horizon, $t \in [0,T]$, an initial infestation level, $\theta_i(0)=\theta_{i,0}$, and a free terminal level of infestation, agent *i*'s problem is:

$$\begin{aligned}
&\max_{\mathbf{w}} \int_{t=0}^{T} e^{-r_i t}\left[p(t)\bar{S}(1-\theta_i(t))-(a\theta_i(t)w_i(t)+bw_i(t)^2)\right]dt \\
&\text{s.t.} \\
&\dot{\theta}_i(t)=\rho_i\theta_i(t)-w_i(t)\left(1+\gamma_i w_j(t)\right)+\sigma_i\bar{S}_i(1-\theta_i(t))+\phi_i(\theta_j(t)-w_j(t))+d_i, \\
&\theta_i(0)=\theta_{i0},\ \theta_i(T)=\mathit{free}
\end{aligned} \tag{7}$$

The associated Hamiltonian is:

$$\begin{aligned}
H = {} & e^{-r_i t}\left[p(t)\bar{S}(1-\theta_i(t))-(a_i\theta_i(t)w_i(t)+b_iw_i(t)^2)\right] \\
& +\lambda_i(t)\left[\rho_i\theta_i(t)-w_i(t)\left(1+\gamma_i w_j(t)\right)+\sigma_i\bar{S}_i(1-\theta_i(t))+\phi_i(\theta_j(t)-w_j(t))+d_i\right]
\end{aligned} \tag{8}$$

Agent *i*'s necessary conditions for an interior solution include:

$$H_{w_i}=e^{-r_i t}(-a_i\theta_i(t)-2b_iw_i(t))-\lambda_i(t)(1+\gamma_i w_j(t))=0, \tag{9}$$

$$-H_{\theta_i} = \dot{\lambda}_i(t) = e^{-r_i t}\left(p(t)\bar{S}_i + a_i w_i(t)\right) - \lambda_i(t)(\rho_i - \sigma_i \bar{S}_i) \qquad (10)$$

where (9), the dynamic optimality condition, can be rearranged to describe user cost;

$$\lambda_i(t) = -\left(\frac{e^{-r_i t}\left(a_i\theta_i(t) + 2b_i w_i(t)\right)}{1+\gamma_i w_j(t)}\right) < 0,$$

which is as would be expected since the stock of invasive weeds, θ_i, is a bad. The sign on $\dot{\lambda}_i(t)$ will depend on the signs and magnitudes of the two expressions on the right hand side of (10), which are the discounted marginal value of the objective function, given a change in the infestation level, $\left(e^{-r_i t}\left(p(t)\bar{S}_i + a_i w_i(t)\right)\right)$, and the value of the marginal change in the infestation level with respect to the infestation level, $\left(\lambda_i(t)\left(\rho_i - \sigma_i \bar{S}_i\right)\right)$. The discounted marginal value is unequivocally positive. The value of the marginal change in the infestation level depends on whether the impact on the growth of the invasive from the existing infestation level (ρ_i) is greater than, equal to, or less than the impact on growth from grazing, $(\sigma_i \bar{S}_i)$. Therefore;

$$\dot{\lambda}_i(t)\begin{cases} >0 \text{ if } & \rho_i \ge \sigma_i \bar{S}_i \text{ or } \\ & e^{-r_i t}\left(p(t)\bar{S}_i + a_i w_i(t)\right) > \lambda_i(t)(\rho_i - \sigma_i \bar{S}_i) \\ =0 \text{ if } & e^{-r_i t}\left(p(t)\bar{S}_i + a_i w_i(t)\right) = \lambda_i(t)(\rho_i - \sigma_i \bar{S}_i) \\ <0 \text{ if } & e^{-r_i t}\left(p(t)\bar{S}_i + a_i w_i(t)\right) < \lambda_i(t)(\rho_i - \sigma_i \bar{S}_i) \end{cases} . \qquad (11)$$

Taking the time derivative of (9) and solving for $\dot{w}_i(t)$ yields the change in the response function for agent *i*. That is;

$$\dot{w}_i(t) = \frac{1}{2b_i}\left[r_i\left(a_i\theta_i(t) + b_i w_i(t)\right) - a_i\dot{\theta}_i - e^{r_i t}\dot{\lambda}_i(t)\left(1+\gamma_i w_j(t)\right) - e^{r_i t}\lambda_i(t)\gamma_i \dot{w}_j(t)\right]. \quad (12)$$

Similarly, the change in agent *j*'s response function is;

$$\dot{w}_j(t) = \frac{1}{2b_j}\Big[r_j\big(a_j\theta_j(t) + b_j w_j(t)\big) - a_j\dot{\theta}_j - e^{r_j t}\dot{\lambda}_j(t)\big(1 + \gamma_j w_i(t)\big) - e^{r_j t}\lambda_j(t)\gamma_j \dot{w}_i(t)\Big]. \quad (13)$$

At this level of generality the signs on (12) and (13) cannot be determined unambiguously. Instead, we turn to dynamic simulation in order to determine the optimal effort paths for agents *i* and *j*. Equations (12) and (13) along with equations (6), (9), and (10) (for both agents *i* and *j*) provide the basis for our numerical simulations.[8]

4.0 Dynamic Simulations

We parameterize the dynamic model from the previous section and simulate to capture the characteristics of Yellow Starthistle (YST) and its potential impact on management strategies for cattle ranching in western states.

YST entered the US in the early 1800's via contaminated alfalfa seed from Eurasia and was first documented in California (CA) in 1824 and has migrated eastward. YST is found in 41 of the contiguous states and is reported as invasive in natural areas in six states. (Murphy, 2005).

The future potential impact of YST on western ranching could be substantial. Consider the case of CA, where the spread of YST increased over *one thousand percent* between 1958 and 2002 (estimated infested acreage increased from about one million in 1958 to over 15 million acres by 2002 (Pitcairn *et al.* 2006). Eighty-five percent of CA counties report YST (NRCS 2006). Total losses of livestock forage in CA due to YST infestation are estimated to be almost $8 million annually. Add this to the estimated, annual out of pocket costs to CA ranchers for control of YST of almost $9.5 million and it is evident that YST has a considerable impact on the grazing livestock sector (Eagle *et al.* 2006). In addition to CA, Oregon, Washington and Idaho have high levels of YST infestations with 72%, 66%, and 62% of counties, respectively, reporting occurrences. The level of occurrence is much lower in other western states. For example, Nevada reports the presence of YST in almost 30% of counties; New Mexico reports about 18% of counties; Wyoming about 8%; and Colorado about 3% (NRCS 2006).

The rapid spread of YST can, in part, be attributed to its characteristics. It is a winter annual that germinates in the fall. In early summer, long stocks with bright-yellow, spiny flowers appear. The dried flower heads release seeds during late summer and early fall. A single flower can produce 100,000 seeds (Eagle *et al*. 2006). There is a high viability rate and the seeds can remain productive for up to a decade. The seeds are easily dispersed through human and animal activity, as well as through water and short distance wind transport. The viability of the seeds can be impacted by the climate and elevation.[9]

YST can be especially problematic in pastures and rangeland. While it is edible by cattle during early stages of growth the spines on the yellow flowers are long, resulting in cattle avoiding grazing even near the plant. Cattle forced to eat the plant at this stage can also sustain injury (Shelley *et al*. 1999). Barry (1995) estimates that there is less crude protein and digestible nutrients in infested rangeland than in un-infested acreage. This reduces carrying capacity and productivity of land.

Considering the progression of YST across the western US, its' impact on rangeland; its current low-level presence in many states; the attributes of rangeland in the states; and the importance of cattle ranching to state economies, it is an important invasive weed to consider.

While the spread of YST may be slower in other western states than was seen in CA, the economic impact could be considerable, making the management choices just as germane. For example, consider New Mexico (NM) where, according to the USDA 2007 Agricultural Census, over 85% of agricultural land is in pastureland and rangeland. Beef cattle account for over $570 million, or about 35%, of the total value of NM livestock and their products sold. The value from this sector is second only to that of the dairy industry. The contribution of beef cattle in other western states is even higher. In Colorado, 77% of the total value of livestock and products sold is attributed to beef cattle, while in Wyoming the figure is 85%.

Western cattle ranching is an industry of contrasts. Depending on the location of the ranch, the size could vary from a few acres to several thousand acres. Land may or may not be irrigated. Elevation, precipitation, and vegetation also vary greatly. Many of these factors can contribute to the carrying capacity of the land. And finally, ranchers are a diverse lot culturally and economically.[10]

What are the optimal strategies for western ranchers? We parameterize the model developed in the previous section to reflect the growth of YST and ranching conditions found in the western US. Table 1 provides the baseline parameters.

[TABLE 1 APPROXIMATELY HERE]

4.1 Baseline Results. First we consider the growth of the invasive when there is no human activity, using the specification in (6) and relevant parameter values from table 1. Figure 1 shows the growth of the stock of the invasive. In the initial year, the only source of the invasive is the 0.5% from community diffusion. Assuming no grazing activity or weed management effort, the intrinsic growth rate, coupled with community diffusion results in a 100% infestation by year 22**.**

[FIGURE 1 APPROXIMATELY HERE]

For our baseline simulations, we first consider symmetric agents over a range of initial infestations. Specifically, we consider 10%, 20%, 30%, 40%, and 50% initial infestation levels. These are the equivalent of beginning a management program in approximately years 12 (10%), 15 (20%), 17 (30%), 18 (40%), or 19 (50%) - from figure 1.

Figures 2 and 3 present the optimal effort paths and resulting infestation levels, respectively, for one of our symmetric agents under these initial infestation levels. While the effort paths in figure 2 are similar in profile, it is notable that at lower levels of infestation, the optimal beginning level of effort is closer to the initial level of infestation, while at higher initial levels, the optimal initial effort is substantially less than the initial infestation level. With the exception of the 10% case, we find that all of the effort paths converge to almost identical levels in the later years. In all cases, as indicated in figure 3, the resulting infestation levels decline in the early years with the optimal effort. In later years, there are increases in the infestation levels, due to reduced effort and the impact of the diffusion of the weed from general community activity.

[FIGURE 2 APPROXIMATELY HERE]

[FIGURE 3 APPROXIMATELY HERE]

In all cases, the infestation is managed. The impact on profitability, however, is substantial. Table 2 provides information on cumulative NPV, average per acre cost over the time frame, and a range of annual costs. All dollar amounts are in discounted dollars. Note that in general the lower the initial level of infestation, the more aggressive the initial effort (relative to the infestation level). At an initial infestation of 10%, the optimal initial effort level is to eradicate 90% of the infestation, whereas when the initial infestation level is 50%, the optimal initial effort eradicates only 78% of the initial infestation.[11] This illustrates the trade-off between the increasing costs of effort and the impact on productivity of the infestation level. Rather than attempting to eradicate the invasive in the initial period, a less aggressive initial approach yields a higher cumulative NPV. As would be expected, higher per acre costs coincide with higher initial infestation levels. Cumulative, discounted NPV is, as would be expected, inversely related to the initial level of infestation. Comparing the NPV for the 10% versus the 50% initial infestation, we see a decline in NPV of over 60%. Obviously, the longer the infestation goes without effort to mitigate or eradicate, the more constrained the agent is in terms of being able to afford the costs of effort.

[TABLE 2 APPROXIMATELY HERE]

Figure 4 plots the change in user cost, $\dot{\lambda}(t)$, and the infestation level, $\theta(t)$ over time for an initial infestation of 10%. The sign on $\dot{\lambda}(t)$ changes over the time period, governed by (11), depending on whether the impact of additional costs today outweighs the future impact. When infestation levels are declining, $\dot{\lambda}(t) > 0$, indicating a decreasing impact on NPV from the invasive, but when the infestation level is increasing, $\dot{\lambda}(t) < 0$, indicating an increasing negative impact on the NPV. Given that $\lambda(t) < 0$, $\dot{\lambda}(t)$ approaches zero from below as terminal time is reached in order to assure $\lambda(T) = 0$.

[FIGURE 4 APPROXIMATELY HERE]

4.2 Varying Carrying Capacity. In much of the southwest, the carrying capacity (CC) on rangeland is very low.[12] We consider the impact of a low carrying capacity by including a scenario of 75 produced pounds per acre (0.1 AU), with symmetric agents. ($\bar{S} = 75$, with all other parameter values equal to those in the baseline, as presented in table 1.) We consider initial infestation levels of 10%, 20%, and 30%. Figure 5 presents the optimal effort paths under low CC for 10% and 20% initial infestation. 30% is not shown, as the optimal effort choice was to do nothing over the time horizon.

[FIGURE 5 APPROXIMATLEY HERE]

The effort paths follow a somewhat familiar pattern of fairly high initial effort levels in order to reduce the level of the invasive weed and then the necessary effort to maintain low levels. This is substantiated by figure 6, which shows the infestation levels under low carrying capacity with 10%, 20%, and 30% beginning infestations. Both the 10% and the 20% infestation levels can be contained even with the low CC. Because it is optimal to exert no effort at an initial 30%, the infestation level increases to the maximum.

[FIGURE 6 APPROXIMATELY HERE]

Table 3 provides a more complete picture of the impact of low CC by the outcomes to the baseline. There are a number of interesting results. First, a low CC results in less effort being expended in the initial period, relative to the baseline, under all three infestation levels. This is to be expected, given that the revenues are lower due to the low CC. But it should be noted that the lower effort levels in the 10% and 20% infestation levels do not result in uncontrollable infestation levels in later periods (as seen in figure 5). While the effort levels are lower, the impact of cattle on weed growth is also lessened because of the lower concentration of AU per acre. The impact on the economic viability of the land is striking. The difference in NPV at an initial 10% infestation is almost $614 per acre less under low CC, while it is over $662 per acre less for the 20% initial infestation. At a 30% infestation, the “do nothing” optimal strategy under low CC results in a decline of $526 per acre over the time horizon.[13]

[TABLE 3 APPROXIMATELY HERE]

Given the results for the 30% infestation case, we ran additional scenarios to find the minimum price necessary for effort to be the optimal choice of the agent. We found that a net price of $0.50 per pound (more than double baseline price) was necessary for effort to be optimal. In this case, an initial effort that eradicated 73% of the weeds in the initial period was optimal. While the weeds were controlled and the NPV over the time horizon was $140, this is a decline of over $410 dollars from the baseline result.

<u>*4.3 Asymmetric Agents*</u>. Now consider asymmetric agents. We assume only the initial infestation levels differ. All other parameter values are the same as presented in table 1. Agent *I* always has an initial infestation level of 10%. Agent *j*'s initial infestation levels are 20%, 30%, 40%, and 50%, across the four simulations. Figure 7 provides traces of the optimal effort paths and corresponding infestation levels for the two agents under the 10%-50% scenario. (The shapes of these paths are illustrative of the paths for the other asymmetric scenarios.) Because agent *j*'s productivity does not suffer from the same level of impact from *i* as when both agents have an initial 50% infestation level, *j*'s initial optimal effort level is lower than in the symmetric case. Agent *i*, however, must contend with the increased impact of *j*'s infestation coupled with *j'*s lower level of activity, which results in higher optimal effort levels in initial periods (relative to the symmetric case) to offset the impact from *j*.

[FIGURE 7 APPROXIMATLEY HERE]

Table 4 presents the asymmetric infestation level results. To see the impact of the asymmetry, we compare the results in table 4 to those in table 2. Examining NPV, there are two facts that stand out as to the impact on agent *i*. First, while agent *i* is not negatively impacted by agent *j*'s 20% infestation level (relative to the symmetric 10% results in table 2), at all other levels of infestation, agent *i* experiences declining NPV and increased average costs due to the impact of agent *j* infestation levels and optimal effort paths. Second, when agent *j*'s infestation levels are 40% or 50%, agent *i*'s optimal initial effort is 100% of the initial infestation.

The impact on agent *j*'s results depends on his initial level of infestation. When *j* has an initial infestation level of either 20% or 30%, his average costs are slightly higher than under the symmetric case and his NPV is slightly lower. However, at 40% or 50%, his average costs are slightly lower and his NPV is slightly higher. In the former case, the synergies from agent *i* are less. This coupled with *j*'s higher infestation level (relative to *i*) result in the higher costs. At the initial infestation levels of 40% and 50%, the relatively smaller impact from *i*'s infestation more than offsets the lower level of effort by *i*. These results begin to illustrate the increased difficulty in invasive species management when agents are asymmetric and that the optimality of a strategy may be situation dependent. For example, the result in Thacher *et al.* (2009) discussed earlier of increasing effort by an agent if his neighbor increases his effort, may be efficient in some cases, but certainly not, as shown in this example, all.

[TABLE 4 APPROXIMATELY HERE]

4.4 Socially Optimal Cooperative Solution. We now consider the cooperative solution for this problem. Applying the cooperative result to NM characteristics illustrates the potential value of information from having the knowledge of the optimal societal outcome.

The socially optimal, cooperative solution for the asymmetric agents illustrates the potential impact of incentive programs. We find the effort paths that result in the highest cumulative NPV's for the two agents. These results are presented in table 5.

In addition to the infestation that is eradicated by the initial effort, the table includes the socially optimal NPV, the cumulative non-cooperative NPV, the difference per acre between the two, the gain to agent *i* and the subsidy required to be paid to agent *j* in order to make agent *j* as well off under the social optimum as under the non-cooperative solution. For the 10%/20% combination, the non-cooperative and cooperative solutions are identical. Under the 10%/30%, 10%/40%, and 10%/50% solutions, agent *i* sees a reduction in the optimal initial effort level and agent *j* sees an increase in the optimal level. Agent *i* sees an increase in his per acre NPV over the time period, while agent *j* requires a subsidy, equal to the discounted total cost of additional effort in order for him to follow the socially optimal effort level.[14] The cooperative solution results in anywhere from a $0.37 per acre increase in NPV over the time horizon to $4.07 per acre. Note the largest difference in the cumulative NPV between the non-cooperative and the cooperative solution is for the 10%/40% infestation level. Thus, the results and strategic management plans are specific to the scenario and a "one-size-fits-all" management solution will likely not be efficient.

[TABLE 5 APPROXIMATELY HERE]

These results can also be used to illustrate the value of information (VoI), such as information about how to identify and treat invasive weeds and the benefit of doing so. The U.S. Department of the Interior, Bureau of Land Management (BLM) (2006) reports that there are over 12.5 million acres of rangeland in NM. BLM and the Society for Range Management (SRM) estimate that almost half of that land or 6 million acres have been degraded by some invasive weeds and that roughly half-a-million acres have been recently restored (BLM 2008). Assuming a rancher occupancy rate of between 50% and 80% on all available rangeland, and alternatively the same rate but only on rangeland that has not been degraded by invasive weeds or that has been restored in NM, it is possible to estimate the value of the information on YST to ranchers in NM. The cumulative non-cooperative result represents the outcome without public dissemination of information on YST. The socially optimal NPV can be thought of as the outcome after public dissemination of information on YST (table 5). The difference between these two values is the value of information in dollars per acre for each infestation level. We assume that acres of rangeland in NM would be equally weighted between various initial infestation levels (10%/20%, 10%/30%, 10%/40%, and 10%/50%). For example, for 10%/30%, there are 3.125 million acres of rangeland. Table 6 shows that the gross VoI is between $20.3 million and $6.6 million.[15]

[TABLE 6 APPROXIMATELY HERE]

4.6 Second-Best with a Myopic Starting Point. The above examples consider the optimal paths over the entire time horizon. In reality, some agents may not exert the optimal level of effort. We consider a simple deviation from the above non-cooperative solution. Agent *j* deviates from the optimal path in *only* the initial time period. Given the sub-optimal starting point the rest of his effort path is optimal, resulting in a second best path. Agent *i*, however chooses the optimal effort taking into account the effort of agent *j*. What is the impact of this single period deviation? For illustrative purposes, we focus on the asymmetric set of agents with agent *i* having an initial infestation level of 10% and agent *j* having an initial infestation level of 50%. We present the results for 0%, 30%, and 50% initial effort levels for agent *j*. These starting effort levels deviate from the optimal by -36, -6, and +14% respectively. In all cases agent *i* chooses the optimal path, given *j*'s strategy. Table 7 presents pertinent results.

If agent *j*'s initial effort level is 0%, the optimal path for this agent for the remainder of the time horizon is also *zero* effort. Agent *i*, however, still finds it optimal to exert effort and in this case, the effort level is 100% of the infestation level over the entire time horizon. Agent *j* makes a profit off of the land in early periods, but the profits decline to zero as the infestations increase and finally the land is abandoned.

If agent *j*'s effort begins at 30% (60% eradication of the initial infestation) agent *i*'s optimal initial effort level is 10% (initial eradication of 100% of the infestation). As would be expected, this is a higher initial effort level than under the non-cooperative solution because *i* has to compensate for lack of initial action by *j*. When *j*'s initial efforts are 50% (eradication of 100% of initial infestation), *i* can reduce his efforts to eradication of 70% of his initial infestation. The impact on the individual agents' NPVs can be substantial. For the zero effort paths, NPVs decline \$261.75 and \$189.73 for *i* and *j* respectively. When *j* begins eradication at a level above the optimum, agent *i* realizes an increase in his NPV of \$5.43 per acre, while *j* loses \$1.61 per acre.

[TABLE 7 APPROXIMATELY HERE]

Finally, we consider the impact of agent *j*'s myopic choice of no initial effort with a 50% initial infestation on agent *i*'s optimal choice as agent *i*'s initial infestation level increases. The question is, at what infestation level does agent *i* find it optimal to do nothing? Somewhat surprisingly, we find that it is optimal for agent *i* to exert effort as long as his initial infestation level is 47% or less. If the initial infestation level is 48% (or greater), the optimal choice is to do nothing.

Again, these scenarios illustrate the value of information. A single miss-step by one agent greatly impacts the outcome for the group.

5.0 Conclusions and Future Directions

We model the management choices of individual agents contending with invasive weeds as a two-state, dynamic game. Parameterizing feedback Nash equilibrium response functions for Yellow Starthistle in New Mexico allows us to simulate the optimal effort paths for cattle ranchers and illustrate the potential trade-offs faced due to the impact of the invasive on the productivity of the land. We present results for symmetric and asymmetric agents. We also compare the non-cooperative and cooperative solutions. With this we consider the potential value of information.

The optimal path is dependent on the beginning states. For a low level infestation, the optimal strategy begins with aggressive effort. As the initial level of the infestation increases, agents find it optimal to be relatively less aggressive in the initial period, illustrating the trade-off between cost of effort today versus the impact on the value of production in the future. Further, we show the impact of carrying capacity on optimal results. Under conditions of low productivity and relatively low net prices, the opportunity to effectively manage invasive species is reduced as is profitability. Specific to asymmetric agents, a high infestation agent situated next to a low infestation agent finds that less initial effort is required (relative to symmetric agents) because of the relatively lower diffusion levels from the neighbor.

The results illustrate the complexity of invasive species management. Heterogeneity of agents, as well as any heterogeneity of the invasive stocks will surely result in a menu of strategies, where the optimal strategy depends on the specific characteristics of the problem. Our results indicate a "one-size-fits-all" management plan for invasive weeds may see successes, but will surely see a number of failures as well.

The scenarios included in this paper represent only a tiny portion of those that are relevant. Differences in diffusion levels, animal units, price paths, effort costs and management time horizons are but a few of the extensions to be explored. In order to focus on the economics of the dynamic game, our model abstracts from more specific models of cattle foraging and conversion to mass, as well as from the ecological models of plant growth. These are clear extensions to the model. In addition, the inclusion of the capital value of the land, as well as considering the effects of uncertainty would provide additional insights.

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Table 1: Baseline Parameters

Parameter	Definition	Base Value
w_i, w_j	Proportion of infestation/acre removed by agent *i* or *j*	Control variables
$\theta_i(0), \theta_j(0)$	Proportion of acre initially infested	State variables
$p(t)$	Net price/pound for beef cattle	\$0.20/pound[16]
$\overline{S}_i, \overline{S}_j$	Carrying capacity for beef cattle on pasture[17]	480 pounds/acre
a_i, a_j	Cost parameter for weed removal treatment[18]	\$500/acre
b_i, b_j	Cost parameter for weed removal treatment	\$500/acre
ρ_i, ρ_j	Intrinsic growth rate of weeds	0.30
σ_i, σ_j	Impact on weed growth associated with grazing	0.0001
ϕ_i, ϕ_j	Proportion infestation due to diffusion from neighboring land	0.10
γ_i, γ_j	Proportion change in infestation from synergies of *i* and *j*'s efforts	0.001
d_i, d_j	Annual diffusion to land from surrounding community	0.005
r_i, r_j	Annual discount rate	5%
T	Terminal time for *i* and *j*	10 years

Table 2: Baseline Results

Initial Infestation (%)	Percent of Initial Infestation Eradicated	NPV (\$)	Average Cost of Effort (\$/Acre)	Cost Range	
				Min	Max (level)
10	90	714.10	2.92	0.00	8.55
20	95	712.75	8.23	0.00	37.05
30	87	552.36	16.20	0.00	72.80
40	83	427.06	27.21	0.00	120.45
50	78	271.27	41.18	0.00	187.58

Table 3: Varying Carrying Capacity

Initial Infestation (%)	Percent Initial Infestation Eradicated Low CC	Percent Initial Infestation Eradicated Base CC	Difference in Initial Period Eradication	NPV (\$) Low CC	NPV (\$) Base CC	Difference NPV (\$)
10	80	90	-10	100.37	714.10	-613.73
20	75	95	-20	50.60	712.75	-662.15
30	0	87	-87	25.92	552.36	-526.44

Table 4: Asymmetric Infestation Results

Initial Infestation (%)		Percent of Initial Infestation Eradicated		NPV ($)		Average Cost of Effort ($/Acre)		Cost Range			
								Min		Max	
i	*j*	*i*	*j*	*i*	*J*	*I*	*j*	*i*	*j*	*i*	*j*
10	20	90	90	714.10	647.84	2.94	8.77	0	0	8.55	34.12
10	30	80	83	711.00	553.97	3.03	15.98	0	0	8.65	68.75
10	40	100	75	708.67	431.24	3.30	26.58	0	0	10.00	121.78
10	50	100	72	707.86	278.56	3.34	40.27	0	0	10.00	192.13

Table 5: Cooperative Solution

Initial Infestation (%)		Percent of Initial Infestation Eradicated		Socially Optimal NPV ($)			Cumulative Non-Cooperative NPV ($)	Change in NPV ($/Acre)	Gain to *i* ($/acre)	Subsidy to *j* *($/acre)*
i	*j*	*i*	*J*	*i*	*j*	*Sum*				
10	20	90	90	714.10	647.84	1361.94	1361.94	--	--	--
10	30	80	90	712.10	553.25	1265.34	1264.97	0.37	$1.10	$0.72
10	40	90	80	713.00	430.98	1143.98	1139.91	4.07	$4.33	$2.09
10	50	90	78	712.42	277.68	990.10	986.42	3.68	$4.56	$3.62

Table 6: Value of YST Information to NM Ranchers (totals in $ millions)

Initial Infestation (%) on Asymmetric Ranches from Table 4		Value of Information (VoI) ($/acre)	VoI with 50% Occupancy on all Rangeland	VoI with 80% Occupancy on all Rangeland	VoI with 50% Occupancy on Un-degraded Rangeland	VoI with 80% Occupancy on Un-degraded Rangeland
10	20	--	0	0	0	0
10	30	0.37	0.6	0.9	0.3	0.5
10	40	4.07	6.4	10.2	3.3	5.3
10	50	3.68	5.8	9.2	3.0	4.8
Total VoI (rounded)			$12.7	$20.3	$6.6	$10.6

Table 7: Agent *j* Myopic, Second-best Paths

% Initial Infestation Eradicated		NPV		Difference from the Non-Cooperative	
***i* Optimal**	***j* Myopic**	***i***	***j***	***I***	***J***
100	0	446.11	88.83	(261.75)	(189.73)
100	60	702.07	239.99	(5.79)	(38.57)
70	100	712.99	276.95	5.43	(1.61)

FIGURES:

[1] The dynamic game theoretic model draws on Martin, *et al.* (1993).

[2] Dot notation is used to designate a time derivative, i.e., $\dot{\theta}_i = \partial\theta_i / \partial t$.

[3] Each agent chooses a best response each period in a sequential process that takes the actions of other agents into account and that in the end they have no incentive to deviate from; but the process is unlike a sequential game in which the agents choose less restrictive behavioral "strategies" that are only Nash equilibria under specific information sets and other rigid requirements.

[4] For an interior solution to hold, the resultant Hamiltonian is concave in w_i and θ_i. That is; $H_{w_i w_i} < 0$ and $H_{\theta_i \theta_i} < 0$. Thus the functions utilized in the model, which include the argument of the state and control, abstract from specific models of cattle foraging and conversion to mass, as well as from the ecological models of plant growth.

[5] Either an acre of land can be used to produce at the optimal carrying capacity or it is avoided by ranchers. We steer away from attempting to model the profitability of range-feeding cattle as a business enterprise. Confinement cattle operations are also used and have in certain circumstances in the past been more profitable, but USDA organic standards for livestock have recently put an emphasis on "free-range" livestock production practices. It is beyond the scope of this paper to consider profit-maximizing beef production input decisions with uncertain and in some situations strategically derived future production conditions.

[6] There is a growing literature on the ecology of rangeland dynamics for agricultural and biodiversity in general and for New Mexico specifically (e.g., http://usda-ars.nmsu.edu, last accessed 10/27/09). However, tractability in the numerical solution of the dynamic game may become an issue.

[7] Note that at some points in time during the growing season there is the possibility that grazing can result in reducing the weed level. However, over a complete growing/grazing cycle (i.e., one season) we impose an inverse relationship between grazing and weed growth.

[8] Stella 8.0 (2003) is used to carry out the simulations.

[9]For more information on YST see, for example, Wilson *et al*. 2003, Shelley *et al*. 1999, or Thomsen *et al*. 1996.

[10] For example, consider NM. While more than 50% of farms and ranches are less than 50 acres in size, almost 20% have more than 1000 acres (NASS 2007). 25% of beef cattle are run on operations of less than 100 head, while more than 20% of beef cattle are run in operations of more than 1000 head. While a majority of ranches are found in the east and northwestern part of the state, almost all counties have some ranches. The larger, more profitable ranches are generally found in the east, while smaller less profitable ranches are found in the southern part of the state. Ranches in the north may be irrigated, while those in the south are most likely not. Carrying capacity varies across the state, but by all standards, the carrying capacity for rangeland is low, given the harsh, dry climate. Culturally, the state is also diverse, which is reflected in the ranching community. Almost 40 percent of farmers in the state are Hispanic or Latino. While many ranchers are fourth and fifth generation, or more, there are others who are first generation, part-time ranchers. NM is not alone in this level of heterogeneity in the ranching community

[11] The 90% and 78% of initial infestation level refers only to the individual agent's actions. The change in the infestation level is, therefore less, due to the other factors in eq (6).

[12] Depending on the agency, carrying capacities on federally leased land in the US vary from 0.04 AU per acre to more than 1.8 AU per acre.

[13]We found 22% is the highest initial infestation level that results in an effort by the agents.

[14] An external source of funding would be required to implement the subsidy.

[15] This does not include an offset for the cost of disseminating public YST information, which is not known. The cost would depend on the information delivery system and the effectiveness of that system. For example, if an effective, existing web-based system could be utilized the costs would be substantially less than if a new information system were required. Thus, our example provides an upper bound on the VoI.

[16] The price of beef cattle has varied substantially over the last several years, as has the cost to produce cattle for sale. We use net price of $20 per hundredweight as our base. This assumes a cost of about $73 per hundredweight to produce and a market price of $93 per hundredweight.

[17] The carrying capacity is based on .7 AU per acre per season.

[18] The cost parameters used in the baseline simulation allow for a large range of costs per acre. The baseline parameters allow for effort costs between $0.50 per acre and $150 per acre. This allows for increasing costs as the infestation level increases and as the level of effort increases, given the type of terrain and management techniques that might be necessary for management in NM.

Figure 1: Unfettered Invasive Growth

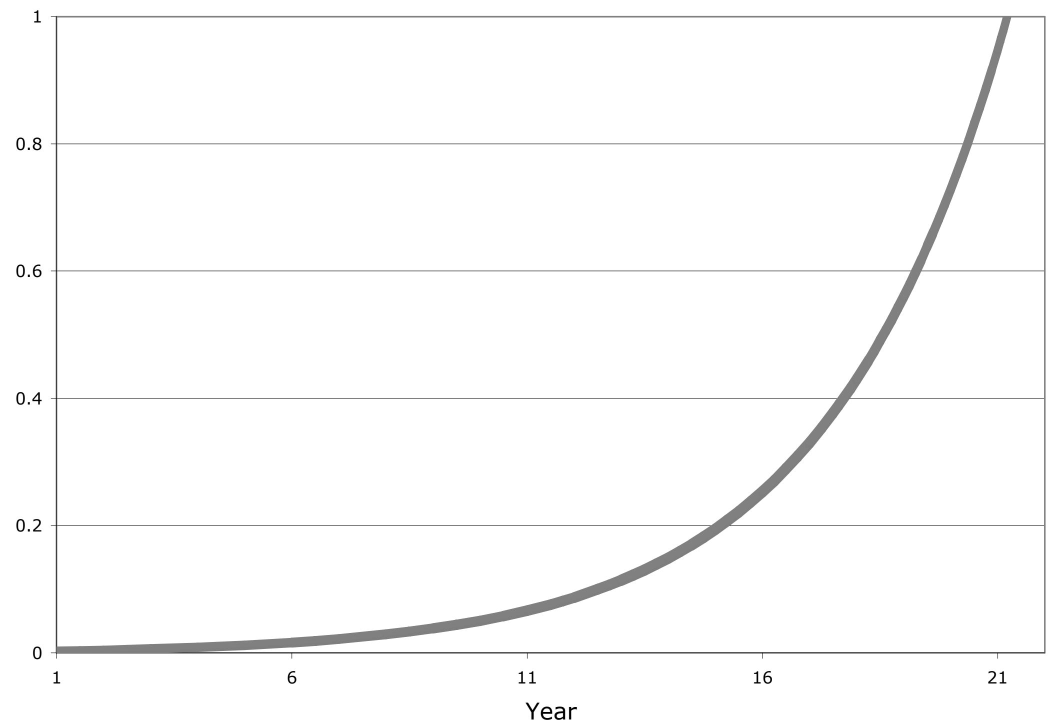

Figure 2: Optimal Effort Paths

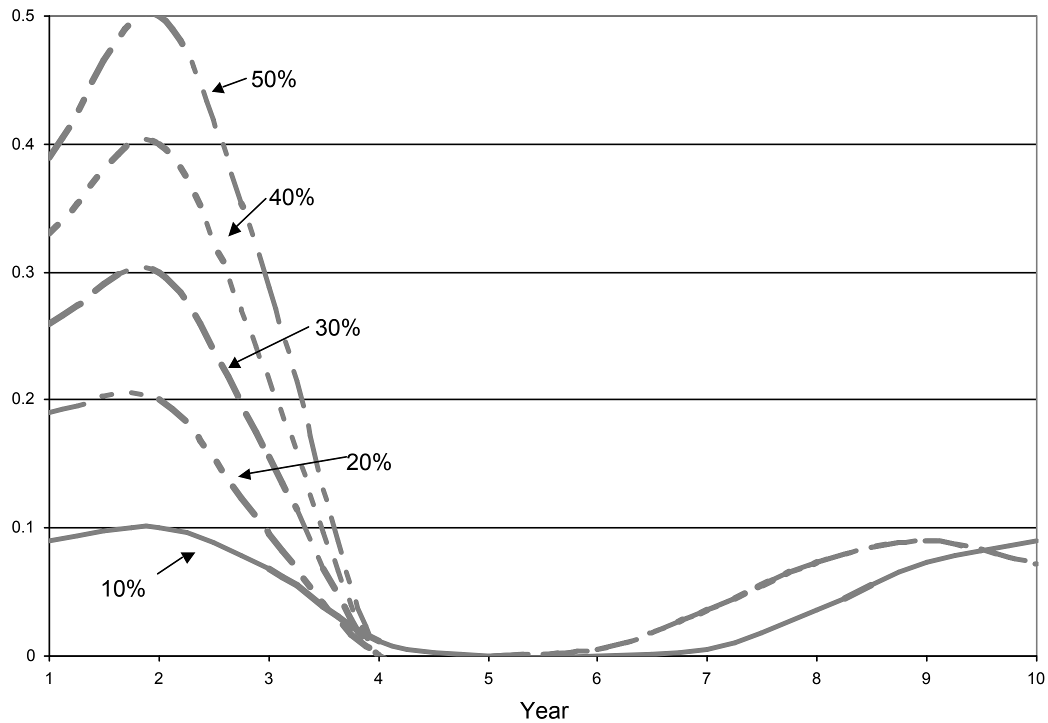

Figure 3: Infestation Levels

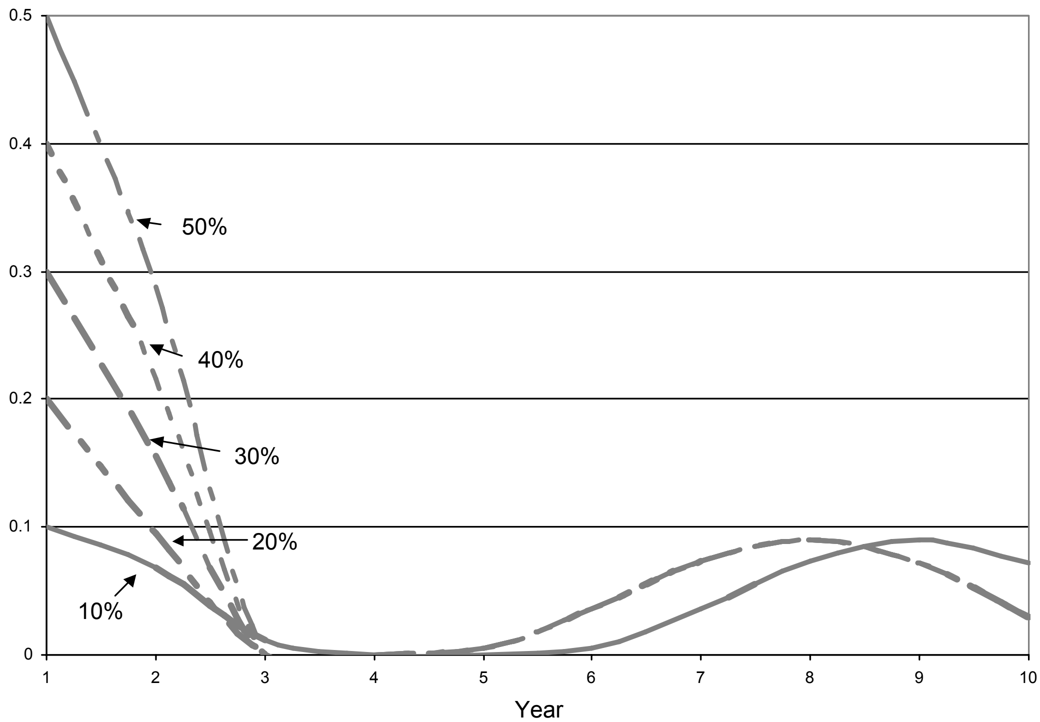

Figure 4: Change in User Cost and Infestation Level

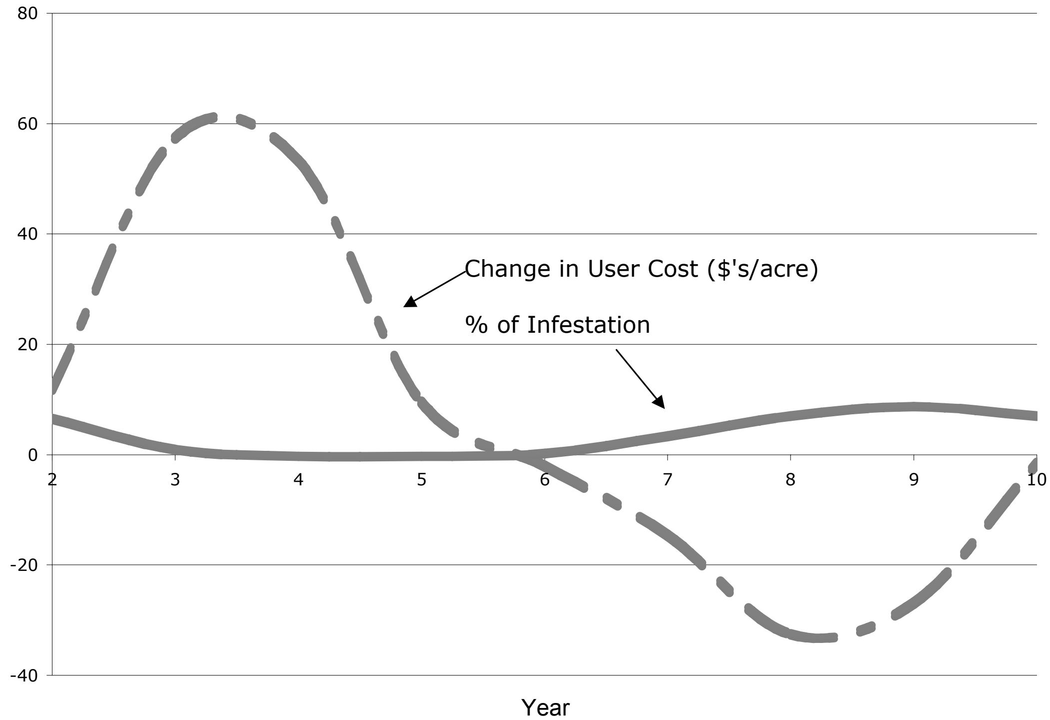

Figure 5: Optimal Effort with Low Carrying Capacity

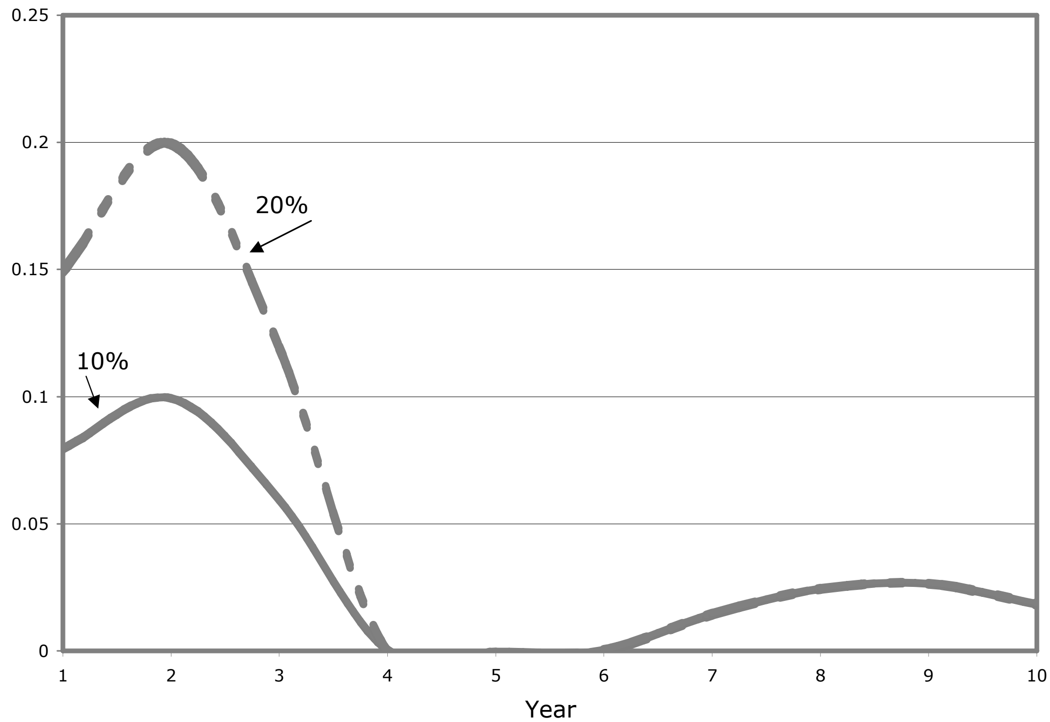

Figure 6: Infestation Levels Under Low Carrying Capacity

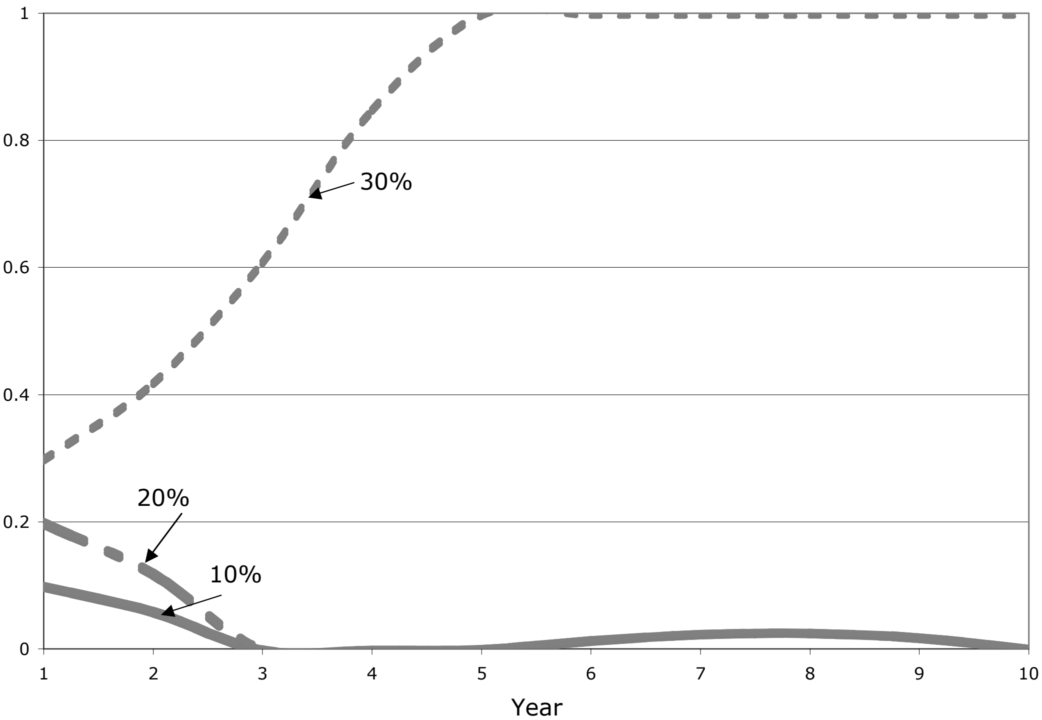

Figure 7: Effort and Infestation Paths for the Asymmetric 10%-50% Case