Fences

The Economics of Connectivity in Spatial Renewables *

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Abstract

This article examines the management of spatially distributed renewable resources—specifically wildlife and infectious diseases—through the lens of economic and spatial analysis. I focus on "bads" like invasive species and diseases, which cause economic and ecological harm, and utilize population control and fencing as central mechanisms. I analyze how fencing influences resource flow and connectivity. On the one hand, in the presence of ecological and economic heterogeneities, fencing can be used to leverage spatial artbitrage opportunities. On the other hand, while promoted as a tool to incentivize the internalization of costs associated with "bads", they may undo what Nature has rightfully done. In this sense, while fencing may be welfare improving in a setting with initially poor connectivity, an uncoordinated use of fencing, although welfare improving, is not welfare maximizing. The study develops a theoretical model that integrates aspects of stock and patch connectivity management and explores both cooperative and non-cooperative management strategies. The findings indicate that optimal management often requires a nuanced understanding of the spatial dynamics and economic costs associated with different control strategies. We present a series of propositions that characterize the conditions under which fencing and resource control strategies can be optimized, including the interaction effects of exclusionary and trap effects. This article contributes to the literature by highlighting the role of spatial heterogeneity in the management of renewable resources and providing insights into the formulation of more effective environmental policies, as it analyzes how to design policies on a subset of the landscape, to maximize economic and ecological benefits.

JEL codes : Q20, Q24, R12
Keywords : spatial resource management, invasive species; fencing and control strategies; optimal management; non-cooperative equilibrium; second-best policy.

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1 Introduction

In the 1600s, the Ma'ohi, the Indigenous People of the Society Islands in French Polynesia (**?**) built vast fish traps, using organic fences, stakes, and poles. On the island of Huahine, stones set vertically, forming V-shaped enclosures trapped schools of fish coming down to sea, from a shallow salt water lake. Fish were pulled towards the sea with the tides, and became trapped in basins. Fish were then harvested using nets in the shallow lake. Managing the fish stock for the community amounted to more than harvesting. Trapping, thus reducing the extent of fish school mobility, was instrumental[1]. Centuries later, in the US populations of white tailed deers have skyrocketted to an estimated 36 million, with exceptionally high densities in the South East (Hanberry and Hanberry, 2020). At high densities, deer populations threaten the regeneration of forests as they influence species composition and abundance through browsing, hence damaging people's properties (Hanberry and Abrams, 2019). Moreover, risks of zoonosis and epidemics increase with large populations. While large scale culling policies have been implemented, landowners have increasingly resorted to other methods, such as repellents, or fencing. Eight-foot or higher woven-wire fences have been used to protect agricultural land such as orchards as well as private homes, to limit the damage done by growing deer populations (Caslick and Decker, 1979). Eventually, during the COVID 19 pandemic between 2019 and 2023, international airports and ports were shutdown, and extensive lockdown policies were implemented worldwide. By avoiding contact between infected and non-infected people, these policies aimed at slowing the spread of the pandemic[2], while managing the extent of the economic losses associated with frozen national and international economies.

These three examples display cases of management of spatially distributed renewable resources. Indeed, fish deer populations, and pandemics grow through time, depending on the size of the population. Moreover, they move through oceans, land, jurisdictions and countries. These examples highlight that the management of spatially distributed renewable resources, whether goods or bads, involves at least two layers : managing the stock, and how it moves through space. Indeed, fishing culling, and curing act as stock management measures, while weirs keep the fish in a given area, repellents and fences keep the deers away, and lockdowns avoid spread from infected to non infected people. Finally, in all cases, policies aimed at managing the movement of the resource are more efficient in one way than the other : weirs avoid outflow of fish, but allows inflow; wildlife exclusion fencing often have doors to let animals escape, and to a certain extent, people were prohibited from entering a country more than leaving one during the COVID 19 pandemic.

First, the decentralized management of spatially distributed renewable resources is made difficult by the spatial externality they generate. When communities compete for mobile fish, they anticipate part of the school to migrate to other communities, and tend to overharvest, as they do not have secure property right over the whole resource through time (Kaffine and Costello, 2010). In the case of deers, free riding on neighbor's culling may deters people to cull the population to efficient levels (Costello et al., 2017). In this sense, patch connectivity, in a non cooperative setting, generates inefficiencies. As a consequence, fences appear as welfare improving, as they diminish patch connectivity and therefore contribute to solving the spatial externality. If a fish stock no longer migrates, communities would tend to harvest it in a more sustainable way. If on a given property, deers have no chance of re-entering, then one may undertake efficient culling measures. However, from a welfare perspective, fencing may undo what Nature has rightfully done. Considering spatial heterogeneity in marginal returns to harvesting or culling, and biological productivity, a resource may flow naturally flow to where it is best managed. In

[1]Modern applications, such as fish fences on Pacific islands, are detrimental to seascape connectivity, and destroy the sea bed, see Exton et al. (2019)

[2]In a given population, where succesive infections are possible, lockdown policies aim at diminishing the basic reproduction number $\mathcal{R}_0$, which measure "expected number of infections generated by a single and (typical) infected individual during their entire infection period" see Saldan and Velasco for a primer SIR modeling applied to COVID 19

this case, although fencing can solve the spatial externality and promote efficient resource use, it would not maximize welfare. Second, spatially distributed renewable resources live on intricate institutional maps, between private and public land and sea. As a result, optimal harvesting and fencing may be difficult to decentralize. Hence, figuring the second best policy mix to best manage spatially distributed renewables is a challenge.

This approach can be viewed as application of the spatial trade literature to ecological networks. For example, Donaldson and Hornbeck (2016) shows that railroads have a global effect, as they change the "market access" of each county, accounting that local changes in "market access" have spillover effects onto other counties. More generally, to understand the general equilibrium effect of domestic policies on international trade patterns, the use of a structural gravity model is inevitable (e.g. 'the new quantitative trade model' e.g. Arkolakis et al. (2012)). However, the gravity equation fails at identifying the impact of country specific determinants of trade flows, e.g. multilateral resistance terms (Anderson and van Wincoop, 2003). In this article, I analyze the changes in local fencing patterns have local and spillover effects, and can be seen as changing multilateral resistance terms in an ecological context, and show how they affect each patch, under various management regimes.

In this article, I focus on the management of "bads", e.g. species that cause economic damages. This includes rodents, feral pigs, deers, or predators in areas where native species prey are threatened. I develop a theoretical model à la Costello et al. (2017), to understand the interplay between stock and patch connectivity management. Species are harvested, grow and disperse through space, according to immutable environmental factors and expenditures that change connectivity, e.g. fences. Fences have two effects : they keep the bad out (*exclusionary* effect), and they keep the bad in (*trap* effect). In what follows, I assume the exclusionary effect dominates the trap effect. In most cases, exclusionary fencing keeps predators, or damaging species out, while allowing entrapped animals to leave the area[3]..

First, I study the optimal policy mix between stock and dispersal rate management. When costs of control are heterogeneous, the sole owner leverages the spatial arbitrage opportunity, and fences only have an exclusionary effect, the sole owner redirects the population stock to where it controled at the cheapest cost. In doing so, she reduces the population in more expensive patches further than when connectivity is absent. Allowing for resource redispatch, she controls more of the species. When fencing has both an exclusionary and trap effect, cost heterogeneity does not suffice to redirect resource. If biological productivity is larger in relatively costlier patches, trapping them can increase the aggregate cost of the invasive species. Therefore, fencing only occurs when biological productivities and control costs are inversely correlated.

Second, I characterize the non cooperative equilibrium in harvesting and fencing. When fencing only displays an exclusionary effect, and fencing is costless, every patch owner fences to the maximum. In doing so, they isolate their patch from the rest of the landscape, and control as if they were isolated from other patches. While this results in a more efficient level of control than in the case of uncontrolled spatial dependence, this is not welfare maximizing : as a matter of fact, the non cooperative equilibrium, while solving the spatial externality, does not leverage the spatial arbitrage opportunity provided by heterogenous costs of controling and biological productivities. When fencing displays (unequal) exclusionary and trap effects, best response functions are non monotonous. In this case, increasing fencing is not always optimal, and the Nash equilibrium results in suboptimal fencing, although closer to the optimal solution.

Third, decentralizing the optimal policy on public and private land may prove impossible. Therefore, I investigate the second best allocation, where some patches of land can enforce the optimal policy mix, while others cannot, and fencing is restricted. I generalize insights from Costello and Polasky (2008) and Costello et al. (2017) to understand how to optimally control the stock and connectivity when

[3]This can be viewed as an ecological version of inward and outward multilateral resistance terms (Anderson and van Wincoop, 2003)

only a subset of patches can be regulated. I show that implementing the first best policy mix, which reshuffles resources to the most cost effective patch is always best. The second allocation is decentralizing an uncoordinated equilibrium, as the spatial externality is resolved and future damages and costs are internalized. However, when a policy maker can only choose 1 instrument, decentralizing optimal fencing with uncoordinated control is the worst outcome, while decentralizing optimal control with uncoordinated fencing is not the worst outcome. Finally, I use a simplified empirical application, using simulated data, to illustrate the optimal control and fencing in the presence of cost and biological heterogeneity, as well as the non cooperative equilibrium. Additionally, I characterize the welfare effects of different management scenarios, depending on the starting policy ground.

This article proceeds as follows : section 2 draws lessons from the existing literature, section 3 explains the models main mechanisms. In section 4, I establish results for the optimal fencing and controling of a public bad, while section 5 looks at the uncoordinated equilibrium. Eventually, section 6 illustrates the findinds, section 7 concludes. Proofs can be found in the appendix (see section 8).

2 Related literature

There is a vast literature that investigates the optimal control, eradication and detection of invasive species (see Epanchin Niell for a review). A much scarcer one looks at the spatial nature of the management of public bads and/or invasive species. Early approaches,Huffaker et al. (1992),Bhat et al. (1996) analyze various management regimes (cooperative, isolated, and coordinated) to deal with the presence of beavers on private land. Movement between patches corresponds to a density dependent pattern, which is, funny enough, an adaptation of Stenseth's "*social fence*" hypothesis Stenseth (1988). In this framework, migration is entirely driven by relative densities. Therefore, optimal stock management needs to account for these migratory effects. With this analysis, Huffaker et al. (1992) and Bhat et al. (1996) limit themselves to two patches, for analytical and computational tractability. A different approach, viewing space as a continuum, has considered options to halt the progression of an invasive species, using barreer zones, to ultimately slow the rate of spread Sharov and Liebhold (1998). While theoretically appealing, this approach may not be suited for operational concerns, whereby optimization on a continuum space is difficult, especially in various directions. In the wake of Brown and Roughgarden (1997), Bulte and van Kooten (1999), numerous models of invasive species have been developed in economics, taking advantage of familiar optimization structures. For example, Blackwood et al. (2010) develop a linear quadratic framework to study the control of an invasive plant species. Taking advantage of the stock independent nature of migration patterns and of the linear quadratic structure, the authors solve the control and prevention problem at a large spatial scale. In more recent work, Costello et al. (2017) develop a large scale model of public bads, characterized by exogenous dispersal, and analyze the potential for eradication in a connected landscape. In doing so, they analyze the effects of varying connectivity parameters, without acknowledging for the potentially endogenous nature of dispersal. Finally, a wealth of papers, in the wake of Sanchirico and Wilen (1999), several papers (Albers et al., 2010; Ambec and Desquilbet, 2012) have investigated the use of policies to halt the spread of invasive species, including mandatory refuges, albeit uniform. While these articles view dispersal as a characteristic that can be influenced, they do not consider the optimal management, or lack thereof, of dispersal. Finally, Janmaat (2005) highlights the role of dispersal in a fishery, and other parameters, to assess the extent of the tragedy of the commons. Interestingly, in that article, Janmaat states that " *until 'fences' are available to contain the 'wandering' offspring, management zones would have to be large. This would minimize the spillover, bringing the incentives of the 'owner' into line with maximizing the total returngenerated by the resource*". The contribution of the article is framed as how to adapt regulation to a given migration pattern. In this article, I reverse the approach for terrestrial species, of sufficient size such that their dispersal can (more or less) be managed. In this article, I build on these frameworks by using a discretized, raster-type landscape, with metapopulation dispersal across patches. Instead of analyzing how policies should adapt to dispersal, and I analyze how policies can shape dispersal, and what happens in the case where management is incomplete.

3 A dynamic spatial model of renewable bads management : fencing and controlling

3.1 Spatial ecology

Assume N patches indexed $i \in \{1, ..., n\}$ with a renewable resource. In a given period, the resource stock X_{it} is harvested by h_{it}, and grows according to the remaining stock, defined as $e_{it} = X_{it} - h_{it}$, such that the pre-migration population in patch i in $t+1$ is $g_i(e_{it})$ such that $g_i'(e_{it}) \geq 0, g_i''(e_{it}) \leq 0$.

Moreover, after the resource grows, it disperses through space (see fig. 1 for a summary of the model timing). This is consistent with continuous metapopulation models (Sanchirico and Wilen, 1999; Bulte and van Kooten, 1999), although discretized (Costello et al., 2017). I assume that dispersal exclusively depends on exogenous, immutable environmental characteristics, and fencing. Density effects on migration rates are not considered in this model.

Dispersal rates between patches depends on directional fencing expenditures in both patches, with $d_{ijt+1} \equiv d_{ijt+1}(f_{it}^j, f_{jt}^i)$, where f_{it}^j measures the amount of fencing in patch i in direction of patch j. The inflow of invasive species from i to j, $d_{ijt+1}(f_{it}^j, f_{jt}^i)$ decreases with f_{jt}^i. I call this the "exclusionary effect": fences keep nuisances out of j. When fencing in i at f_{it}^j, the outflow of invasive species from i to j decreases as well, as species get trapped in i. This effect is the "trap effect" : fences trap the nuisance in. However, in most cases of exclusionary fencing, the exclusionary effect dominates the trap effect, allowing for trapped animals to escape. Fencing reduces the inflow from i to j at a decreasing rate, whether it is undertaken in patch i or j. The rate of patch retention d_{iit+1} is the remainder after migrations from i to j. Dispersal rates are ultimately affected by immutable environmental factors (landscape discontinuities such as roads, rivers, moutains; altitude and terrain ruggedness etc). Eventually, dispersal rates sum to 1. Therefore :

$$d_{ijt+1} : \mathbb{R}^+ \times \mathbb{R}^+ \to [n_{ij}, m_{ij}] \subset [0, 1] \tag{1}$$

$$\underbrace{\frac{\partial d_{jit+1}}{\partial f_{jt}^i}}_{\text{Exclusionary effect}} \leq \underbrace{\frac{\partial d_{ijt+1}}{\partial f_{it}^j}}_{\text{Trap effect}} \leq 0 \tag{2}$$

$$\sum_{j \neq i}^{N} d_{ijt+1}(f_{it}^j, f_{jt}^i) + d_{iit+1} = 1 \tag{3}$$

Where n_{ij}, m_{ij} are the immutable bounds to dispersal rates, and second-order derivatives are (weakly) positive. Finally, connected patches can be seen as a graph with vertices $i \in \{1, ..., n\}$ and directional, weighted edges d_{ijt+1}. Hence, dispersal at the landscape scale can be apprehended using an $n \times n$ matrix $\mathbf{D}_{t+1}$ such that $\mathbf{D}_{t+1}(i, j) = d_{ij+1}(f_{it}^j, f_{jt}^i)$. Each row i of $\mathbf{D}_{t+1}$ represents outflow from i to all patches (including self retention in i) and each column j represents the inflow from all patches to j (including self retention in j).

3.2 Spatial economy

The presence of bads is costly in each patch via two channels, modeled as in Costello et al. (2017). First, the presence of bads implies property specific control expenditures. The larger the stock, the lower the marginal cost of control, hence accounting for a stock effect, where the marginal cost of control $c_i(s)$ is decreasing with stock size, $c_i'(s) < 0$. The total cost of controlling down to residual stock e_{it} is $\int_{e_{it}}^{X_{it}} c_i(s)ds$.

Additionally, the presence of the residual stock causes heterogeneous marginal damages (for example, deers cause more damages to orchards and managed forests than to meadows) $k_i(s)$, which increase with stock size $k_i'(s) > 0$, resulting in convex damages. The total damages caused by the residual stock is $\int_0^{e_{it}} k_i(s)ds$.

Eventually, fencing is costly, with heterogeneous costs (driven by terrain, difficulty of access, type of fence etc) across patches. The marginal cost of fencing $\gamma_i(s)$ is weakly increasing with fencing $\gamma_i'(s) \geq 0$ and $\gamma_i(0) > 0$. The total cost of fencing is $\sum_{j\neq i} \int_0^{f_{it}^j} \gamma_i^j(s)$.

The total cost in each patch i and period t is :

$$C_i(e_{it}, X_{it}, f_{it}^1, ..., f_{it}^j) = \int_{e_{it}}^{X_{it}} c_i(s)ds + \int_0^{e_{it}} k_i(s)ds + \sum_{j\neq i} \int_0^{f_{it}^j} \gamma_i^j(s) \tag{4}$$

The patch-period specific cost depends on current patch specific decisions, as well as past decisions by other agents, which influence the stock of bad in patch i at the beginning of period t.

4 Optimal fencing and controling

Assume a sole owner has to manage patches 1 to N. She can decide how much to control in each patch, as well as to what degree patches are connected to minimize the total cost of the public bad, through time. Her decision problem is akin to choosing how to allocate resources between self insurance and self protection (Ehrlich and Becker, 1972) and being risk neutral. On the one hand, she can decide to insure herself against "bad" states of the world by equalizing the marginal costs of the public bad across patches. On the other hand, she can self protect, and isolate each patch from each other. Because the problem features non linear properties in resource growth, dispersal, and costs, the continuum of options between only controlling the species and only managing the spatial connectivity across patches cannot be linearly interpolated.

Her objective is to minimize the present value of aggregate costs across patches over two periods:

$$V(X_{1t}, ..., X_{Nt}) = \min_{\forall i\{e_{it}, \{f_{it}^j\}_{j\neq i}\}} \sum_{i=1}^{N} C_i(e_{it}, X_{it}, f_{it}^1, ..., f_{it}^j) + \delta V(X_{1-t+1}, ...X_{Nt+1}) \tag{5}$$

4.1 A spatially disconnected world

As a benchmark, if patches were not connected (e.g.$\forall i, j$, $m_{ij} = n_{ij} = 0$, thus $d_{ijt+1}(f_{it}^j, f_{jt}^i) = 0$), the sole owner would control the efficient amount in each patch, such that the current marginal costs of control, net of damages, equal the discounted effect on control costs. Indeed, as patches are not connected, there is no need to take into account the dispersal of the stock between patches, and optimal escapement depends only on patch specific variables. Proposition 1 establishes that fact.

Proposition 1 *If* $\forall i, j$, $m_{ij} = n_{ij} = 0$, *then,* $\forall i, j$ *and* $\forall t$ *:*

$$f_{it}^{j} = 0 \tag{6}$$

$$k_i(\bar{e}_{it}) = c_i(\bar{e}_{it}) - \delta g_i'(\bar{e}_{it}) c_i(X_{it+1}) \tag{7}$$

In this case, each patch owner optimally controls the patch specific population, accounting for a dynamic stock effect : as the population is treated at a lower level, marginal growth is important and lowers the future cost of effort.

4.2 Optimality conditions for interior fencing and escapement

When dispersal can be managed (e.g. when $\exists i, j$ such that $m_{ij} > 0$), the sole owner decides both the levels of fencing and residual stocks. Proposition 2 establishes the conditions for interior solutions to emerge.

Proposition 2 *Interior optimal residual stock in each patch* i *is such that :*

$$k_i(e_{it}) = c_i(e_{it}) - \delta g_i'(e_{it}) \left[c_i(X_{it+1}) + \sum_{j \neq i}^{N} d_{ijt+1}(f_{it}^{j}, f_{jt}^{i})(c_j(X_{jt+1}) - c_i(X_{it+1})) \right] \tag{8}$$

And optimal fencing in patch i *towards patch* j *is :*

$$\gamma_i^j(f_{it}^j) = \delta \left(\frac{\partial d_{ij+1}}{\partial f_{it}^j} g_i(e_{it}) - \frac{\partial d_{jit+1}}{\partial f_{it}^j} g_j(e_{jt}) \right) \big(c_i(X_{it+1}) - c_j(X_{jt+1}) \big) \tag{9}$$

See proof in appendix 8.1.1

Equations 8, 9 define stock independent solution : the solutions emerging from the first order conditions do not depend on the state $\mathbf{X}_t$. The optimal residual stock in patch i is such that the current marginal damage caused by letting the marginal unit matches the corresponding control cost, mitigated by the discounted global cost effect, as in Costello et al. (2017) (refered to as the *dynamic marginal cost effect*). When a marginal unit of bad is controlled, marginal damage $k_i(e_{it})$ are not incurred in patch i. This marginal damage has to equal the current period cost of controling $c_i(e_{it})$, and the discounted next period cost. A marginal unit of bad will grow according to $g_i'(e_{it})$, and disperse through space. A portion $d_{iit+1} = 1 - \sum_{j \neq i} d_{ijt+1}(f_{it}^j, f_{jt}^i)$ remains in the patch (and sets the marginal cost of control at $c_i(X_{it+1})$, while a fraction goes in each connected patch j, incurring a decrease in marginal control costs of $c_j(X_{jt+1})$. The extent of control thus depends on the current marginal damages and costs, and the spatial dynamic component. If dispersal to neighbors is *naturally* large, and the marginal cost of treatment tends to be lower in these patches, escapement increases, leveraging a spatial arbitrage opportunity.

Interior fencing is a novel result. In a given patch, the sole owner fences such that the current marginal cost of fencing equals the discounted marginal benefits of doing so. The sole owner fences to leverage a spatial arbitrage opportunity. First, the *exclusionary effect* has to outweigh the *trap effect* in the pairwise resource flow: more population has to be marginally left out than trapped in following fencing. Second, as the pairwise resource flow increases towards B, it is beneficial to fence only if this comes at a cheaper control cost in patch j than in patch i.

In the next subsections, I analyze the different effects at play here separately. Namely, as the control cost is heterogeneous and stock dependent, I analyze both implications.

4.3 No fencing in the absence of spatial arbitrage opportunity

The spatial arbitrage opportunity arises from the difference in control costs across space and for different stock levels. In the absence of cost heterogeneity across space or levels, marginal control costs are linear and homogeneous. In that case, the absence of control cost heterogeneity implies no fencing : redirecting the resource flow has no interest, since there is no additional cost reduction to be expected. Although patches are connected, there is no heterogeneity to leverage. As a consequence, the optimal control rule is independent of dispersal. In this case, the discounted future cost of controlling the increased stock in patch i equal the current costs net of damages. Moreover, the optimal control does not depend on spatial dispersal, as the cost of control are homogenous, and depends only on patch specific characteristics. In this specific linear case, the equilibrium collapses to the disconnected optimal control strategy defined in proposition 1.

Proposition 3 *With (i) linear homogeneous control costs (e.g. $\forall i,\ c_i(s) = c$), optimal management consists in no fencing $\forall i, j,\ f_{it}^{j} = 0$ and optimal escapement is implicitly defined by eq 7 e.g.*

$$c\delta g_i'(e_{it}) = c - k_i(e_{it})$$

See proof in appendix 8.1.3

In most real life applications, the marginal costs of control depend on the population size in the beginning of the period. Moreover, they do display spatial heterogeneity at equivalent size. In this case, positive fencing is among the strategies to maximize welfare.

4.4 Optimal management with exclusionary effect and free fencing

Assume control costs are heterogeneous, such that $\forall s,\ c_j(s) < c_i(s)$[4]. In this case, there is a potential to levy a spatial arbitrage opportunity : if the stock were more directed towards patch j, larger levels of control could be undertaken with the same budget (or equivalently, the same amount of aggregate control could be undertaken at a lower cost).

In this example, I assume fencing only has an exclusionary effect. In real life, exclusionary fencing is a common practice in conservation. For example, the Kilauea Point National Wildlife Refuge in Hawaii has implemented a predator exclusion fence to protect native seebirds from mammalian predations[5]. I focus on the case where exclusionary fences allow the population to escape[6].

In patch i, if fencing only has an *exclusionary effect* and no *trap* effect, fencing keeps the stock from j out, while allowing the stock from i to escape. Upon fencing, the sole owner gains clear marginal benefits, as the stock that used to flow from j to i no longer does, and the stock can still flow from i to j, reducing the total cost. In this case, the sole owner has an interest in reshaping how the stock moves through space, and thus, to reshape the spatial externality, such that resources flow to patch j.

Assume fencing is free, e.g. $\forall i, \gamma_i(\cdot) = 0$. To fix ideas, assume there are only 2 patches, A and B, such that control is cheaper in B. Moreover, assume a flat landscape, with homogeneous environmental conditions, such that the dispersal can be managed to the full extent. Several cases arise depending on the cost heterogeneity among patches. Optimal management reshuffles the resource among patches such that the marginal costs are equalized : the spatial arbitrage opportunity is exhausted. However,

[4]Admittedly, this is a restrictive assumption, that I will change in future versions of this article. Indeed, it restricts the realm of potential cases by assuming away crossing. The qualitative nature of the findings still shed important light on the phenomenon at stake

[5]The 11,200 foot fence protects 168 hectares of wildlfe habitat and even includes underground skirt and curved hood to avoid climbing over or digging under, see https://www.fws.gov/story/2023-08/pacifics-largest-predator-exclusion-fence

[6]In this case, the fencing technology can be seen as akin to an electrical resistance

when marginal costs are very heterogeneous, a sole owner would do two things : keep all of the resource incoming *from B to A outside of A*, and place no restrictions on the flow *from A to B towards B*, such that the spatial arbitrage opportunity is managed to the full of its extent.

Proposition 4 *If (i) control costs are heterogeneous ($c_B(s) < c_A(s)$) and $Im(c_B) \cap Im(c_A) \neq \emptyset$:*

$$\begin{aligned}
&\{f^B_{At}, f^A_{Bt}\} \equiv c_A(X_{At+1}) = c_B(X_{Bt+1}) \\
&e_{At} = \bar{e_{At}} \\
&e_{Bt} = \bar{e_{Bt}}
\end{aligned}$$

Second, if (ii) $\min c_A(s) > c_B(0)$ and (iii) dispersal from A to B can be fully managed (e.g. $n_{AB} = n_{BA} = 0$ and $m_{AB} = m_{BA} = 1$, then :

$$\begin{aligned}
&f^B_{At} \to \infty \Rightarrow d_{BAt+1}(f^A_{Bt}, f^B_{At}) = 0 \\
&f^A_{Bt} = 0 \Rightarrow d_{ABt+1}(f^B_{At}, f^A_{Bt}) = 1 \\
\\
&k_A(e_{At}) = c_A(e_{At}) - \delta g'_A(e_{At}) c_B(X_{Bt+1}) \\
&\iff e_{At} < \bar{e_{At}} \\
&k_B(e_{Bt}) = c_B(e_{Bt}) - \delta g'_B(e_{Bt}) c_B(X_{Bt+1}) \\
&\iff e_{Bt} = \bar{e_{Bt}}
\end{aligned}$$

see proof in appendix 8.1.4

Proposition 4 establishes that when fencing only has an exclusionary effect, is free and dispersal can integrally be managed, the sole owner uses fences to redirect the resource. Thus she exhausts the spatial arbitrage opportunity, and equates the dynamic marginal costs among patches. However, when costs are very heterogeneous, it is worth redirecting all of the resource to the cheapest patch. In this case, control increases in patch A, benefiting from the reshuffling of the resource. Moreover, management in B is the same as if there were no dispersal (see proposition 1), as there is no dispersal from B.

The sole owner can choose management to equate returns across space. When there is a spatial dependence, and connectivity is fixed by natural parameters, patches with high marginal costs of control, control less than in the no-dependence case. Symmetrically, patches with low marginal costs of control control less when they are not connected, as they can benefit from the dynamic marginal cost effect with population inflow from other patches. When the extent of connectivity can be managed (e.g. $n_{ij} > 0$ and $0 < m_{ij} \leq 1$), fencing arises in high control cost patches, and is kept at the minimal level in low control cost patches. In doing so, escapement decreases in high cost patches, and increases in low cost patches.

Proposition 5 *If fences are free and only have an exclusionary effect, fences and control are substitutes see proof in appendix 8.1.7.*

4.5 Optimal management when fencing displays exclusionary and trap effects

Assume now that fencing only has a trap effect. For example, small scale fencing has long been used in the US to manage feral pigs populations, where animals get entrapped, but more can come in[7]. In patch A, if fencing only has a *trap effect* and no *exclusionary* effect, fences keep the stock inside of A, while they do not reduce the inflow from patch B. As costs of control are smaller in B than in A, a sole owner

[7]see https://www.aphis.usda.gov/sites/default/files/managing-feral-pigs.pdf

would benefit from keeping the population in B where it is cheaper to control, and let the population from A get trapped in B. The mechanism described here is *in fine* symmetrical to the *exclusionary* case, but fences are located in B.

In most cases, fences has a both an *exclusionary* and *trap* effect, e.g. fencing reduces the stock inflow from other patches to a given patch A, and reduces the stock outflow from patch A to other patches. Following equation 9, two effects are at play. First, fencing still results from a spatial arbitrage opportunity. When costs are heterogeneous, pairwise fencing arises only in the patch with the lower control cost. Second, the interplay between the *exclusionary* effect and the *trap* effect is key for fencing to be welfare improving.

To build intuition, assume fencing is free, and marginal fencing costs are constant but heterogeneous. First, if

Proposition 6 *When fencing has both an exclusionary effect and trap effect, with (i) heterogeneous costs of fencing, (ii) free fencing across patches, positive fencing occurs in patch i if:*

1. *$c_i > c_j$ and the exclusionary effect dominates the trap effect :*

$$\left| \frac{\partial d_{ijt+1}}{\partial f_{it}^j} g_i(e_{it}) \right| < \left| \frac{\partial d_{jit+1}}{\partial f_{it}^j} g_j(e_{jt}) \right| \tag{10}$$

2. *$c_i < c_j$ and the trap effect dominates the exclusionary effect :*

$$\left| \frac{\partial d_{ijt+1}}{\partial f_{it}^j} g_i(e_{it}) \right| > \left| \frac{\partial d_{jit+1}}{\partial f_{it}^j} g_j(e_{jt}) \right| \tag{11}$$

And optimal fencing is determined with $\frac{\partial d_{ijt+1}}{\partial f_{it}^j} g_i(e_{it}) = \frac{\partial d_{jit+1}}{\partial f_{it}^j} g_j(e_{jt})$

Conclusion about escapement level?
See proof in appendix 8.1.8

Proposition 6 states that fencing in patches i depends on control cost and biological productivity heterogeneity. Indeed, assume patch j is controling the stock at a cheaper cost than patch i ($c_j < c_i$). A naïve argument would call for fencing in i as long as the rate at which fencing decreases inflow from j is larger than the rate at which fencing increases self retention in j. However, population levels matter. Indeed, if population growth is sufficiently high in i, the self retained population in i may be very large, even though the rate of self retention increases at a slower pace than the rate of inflow from j decreases. Overall, if the pair of costs through space is inversely correlated with the pair of biological productivities, fencing appears as optimal in patch i, and in patch j. Proposition 7 establishes the effect of biological heterogeneity for management.

Proposition 7 *Establish previous claim : if biological productivity in patch i is such that*

$$\min_s g_i(s) > \max_s \frac{\frac{\partial d_{jit+1}}{\partial f_{it}^j}}{\frac{\partial d_{ijt+1}}{\partial f_{it}^j}} g_j(s)$$

the spatial cost heterogeneity is not enough to warrant fencing, as biological productivity is so large that the trap effect always dominates.
Further characterize that with the correlation between cost function and growth.

Finally, when control costs are stock dependent, the spatial arbitrage opportunity can be exhausted when either costs of control are equalized across patches, or when the exclusionary effect equals the trap effect. In the former case, the result on optimal escapement remains unclear, while in the second case, it has been characterized to replicate the disconnected equilibrium.

5 Decentralized management and non cooperative behavior

In most cases, management of invasive species is decentralized and let to individual landowners. To characterize the interplay of optimal policy on a subset of the landscape and deccentralized management, I study the decentralized management of the bad. First, I analyze the simplified case where fencing only displays an exclusionary effect. Second, I generalize the analysis with two way fencing.

An individual patch owner tries to minimize the intertemporal sum of damages and control costs, without accounting for the spatial externality :

$$V(X_{it}) = \min C_i(e_{it}, X_{it}, f_{it}^1, ..., f_{it}^j) + \delta V(X_{t+1}) \tag{12}$$

5.1 Non cooperative management with exclusionary fencing

Each patch owner tries to minimize its own intertemporal control costs and damages. In this section, I assume that fencing is costless $\gamma_i(\cdot) = 0$, As in section 4.4, the only driver of fencing here is cost heterogeneity. In this case, as fencing is free, and there is no trap effect, each patch owner fences to the maximum in each direction. In doing so, the non cooperative equilibrium results in no patch connectivity. Each patch is controled as in the spatially disconnected equilibrium.

Proposition 8 *If (i) fencing only displays an exclusionary effect, and (ii) fencing is free, the Nash equilibrium is such that :*

$$\forall j \neq i, \tilde{f_{it}^j} \to \infty$$
$$\tilde{e_{it}} = \bar{e_{it}}$$

If (iii) control costs are heterogeneous, the Nash equilibrium is sub-optimal
See proof in appendix 8.1.10

Fencing solves the spatial externality. In doing so, each patch owner controls the stock as in the non spatially connected world. While this appears as a desirable solution, it is not welfare maximizing. Indeed, resolving the spatial externality amounts to forgoing the potential spatial arbitrage opportunities from optimal fencing. As a matter of fact, dynamic marginal costs of control are not equalized across patches, unless there is no cost heterogeneity.

When fencing is costly, individual patch owners reduce the inflow from neighbors until the discounted additional cost from inflow equals the marginal cost of fencing. In this case, the spatial externality is managed, but it is not optimally managed : there is too much fencing relative to the optimal, and the population flow is not properly distribtued to minimize aggregate costs.

Proposition 9 *When fencing is costly, the Nash equilibrium results in overfencing, and is suboptimal. See proof in appendix 8.1.9*

5.2 General case : fencing with exclusionary and trap effects

The non-cooperative equilibrium results in inefficient provision of fencing and in some cases, under control. Indeed, as each agent does not necessarily internalize the value of spatial connectivity, it overfences.

Determining the Nash equilibrium is still a work in progress and left for a future version of this draft. Nonetheless, optimality conditions are summarized in proposition

Proposition 10 *Optimal fencing $\tilde{f_{it}^j}$ and control $\tilde{e_{it}}$ in a non cooperative setting, $\forall i$:*

$$k_i(\tilde{e_{it}}) = c_i(\tilde{e_{it}}) - \delta g_i'(e_{it})c_i(X_{it+1})\left(1 - \sum_{j\neq i} d_{ijt+1}(\tilde{f_{jt}^i}, \tilde{f_{it}^j})\right)$$

$$\gamma_i^j(\tilde{f_{it}^j}) = \delta\left[\frac{\partial d_{ijt+1}}{\partial \tilde{f_{it}^j}} g_i(\tilde{e_{it}}) - \frac{\partial d_{jit+1}}{\partial \tilde{f_{jt}^i}} g_j(\tilde{e_{jt}})\right] c_i(X_{it+1})$$

Proposition 10 implictly defines a system of best response functions. It is difficult to characterise it so far, without imposing more structure. Note that with positive costs, the Nash equilibrium of full fencing no longer holds. Moreover, the best reaction fencing may not be monotonous : at a given level, it may be optimal to decrease own fencing, to diminish the trap effect a neighbor j imposes on a patch owner i. However, for larger levels, it may be optimal to keep increasing, to counteract the trap effect with an exclusionary effect.

6 Numerical Application - a second best world

In this section, I illustrate the model with a small scale landscape, with only two patches. I characterize the optimal levels of harvest and fencing, as well as the non cooperative equilibrium. Moreover, I look at the interplay between a public land, where optimal policy levels can be implemented, and a private land, where policy levels cannot necessarily be implemented.

6.1 Growth, dispersal, and costs

In what follows, I assume constant marginal costs of control and marginal damages. Moreover, I normalize the stock in each patch to be such that $X_{it} \in [0, 1]$. Species in each patch grow according to a heterogeneous growth function, with biological production elasticity α_i :

$$g_{it}(e_{it}) = e_{it}^{\alpha_i} \tag{13}$$

In what follows, $\alpha_i = 0.8$.

Second, dispersal is given by :

$$d_{jit+1}(f_{jt}^i, f_{it}^j) = (m_{ji} - n_{ji})\exp(-(f_{it} + \beta_j^i f_{jt})) + n_{ji} \tag{14}$$

With $m_{ij}, n_{ij} \in [0, 1]$ the immutable bounds to connectivity, and β_j^i the cross effect of neigbor's fencing. In what follows,$\forall i, j$; $m_{ij} = 1$ and $n_{ij} = 0$. Additionally, I focus on exclusionnary fencing, such that $\beta_j^i = 0$.

Finally, I focus on a case of linear, yet heterogeneous marginal costs of control, with $c_j < c_i$, and constant marginal damage k.

I take an initial dispersal matrix between the two patches. The idea is that prior to the study period, the study area had a given pattern of connectivity, such that patch A was a sink and B a relative source :

Parameter	value
m_{ij}	1
n_{ij}	0
α_i	0.8
X_0	50
c_A	8
c_B	7
k	2

Table 1: Parameters

$$\mathbf{D}_1 = \begin{pmatrix} 0.7 & 0.3 \\ 0.8 & 0.2 \end{pmatrix} \tag{15}$$

7 Discussion and conclusion

In this article, I analyze the interplay between deciding how to let a public bad disperse through heterogeneous land patches, and how to optimally control it. From a social planner perspective, the existence of economic and biological heterogeneity pave the way to leverage a spatial arbitrage opportunity. Indeed, by reshuffling the resources to the most cost efficient patches, the sole owner can increase control at a reduced cost. Furthermore, in doing so, she adapts her local control strategies, increasing control in the most costly patches, but achieving overall larger control at a lower cost. Based on observed data pertaining to the immutable nature of connectivity bounds, this article opens the way to smart and actionable land planning for biodiversity preservation and invasive species management. Second, the non cooperative equilibrium in controling and fencing reduces the extent of the spatial externality and promotes an individually efficient level of resource control. This result is not robust to both exclusionary and trap effects as of now. Characterizing the best response function in non linear settings is a difficult task, and I still am blocked with that. The question remains to be investigated: does the decentralized management of the extent of spatial connectivity (and hence spatial externality) lead to a suboptimal allocation?

This article is only halfway done.
First, I would like to finalize how to characterize endogenous network formation in a non cooperative setting involving a renewable resource (Bramoullé et al., 2014; Allouch, 2015) Second, I would like to analyze the second best allocation when a subset of patches can be managed by a sole owner, while the other set is let at the decentralized equilibrium. In this setting, I am interested in the second best policies that can minimize the aggregate cost and damages. It is in this respect that I think using methods inspired by the trade literature cited in the introduction could prove useful, to understand how local changes in dispersal influence the distribution of costs and damages through space and time.
I wonder if tools from graph theory can be used to target the most efficient patches for population control or dispersal : the intuition is if dispersal is difficult to manage, patches with largest eigencentrality weighted by population growth should be targeted first for population reduction. If population is difficult to manage, reducing the maximum eigencentrality and reshuffling dispersal to low cost patches appears a sound option.

Third, an empirical application is under preparation, with data on invasive species being collected. The area of analysis could be South East US and the species considered deers, although they do not exclusively respond to the definition of invasive species.

Finally, this article aims at tackling the notions of connectivity and dispersal of species in natural ecosystems. Therefore, natural avenues include revisiting a ”social fence hypothesis” (Stenseth, 1988), or more broadly, stock-dependent net migration rates between patches. Additionally, fences could be considered as a stock, but the use of a flow variable considerably simplifies the analysis. While it aims at studying ecosystems, this article is very simplistic in that it does not consider the multiple functions of an ecosystem, as it focuses on the relationship between connectivity and a single species. Restoring connectivity is of the essence for the survival of species and to halt the global biodiversity decline (Davis et al., 2024) and is at the core of global biodiversity policy[8]. A natural avenue would be to analyze how to weigh connectivity to maximize its benefits while limiting the risks associated with it, in a context of invasive species or pandemics.

[8]The Keunming-Montreal Global Biodiversity Framework, adopted by 195 parties of the Convention on Biological Diversity in December 2022 sets ambitious targets for biodiversity conservation, to halt the overall decline in biodiversity. Goal A and the corresponding targets 1 to 8 set ambitious targets for conservation and ecological restoration, including the famous 30% objective, whereby 30% of land, water, coastal and marine areas are protected by 2030[9]. In more detail, goal A states *"the integrity, connectivity and resilience of all ecosystems are maintained, enhanced or restored [...] Humand induced extinction of known threatened species is halted"*

Quelle est la structure du jeux, comment est prise la décision sur e ou f, est-ce un one time, est ce que le jeu est répété?

Structure: traiter les cas symétriques, ou alors en 2x2, un cas hétérogène à deux agents, avec un peu plus de structure, sinon il y aura des choses contre intuitives.

Trouver des bottlenecks ou des endroits où c'est obligé de passer.

8 Appendix

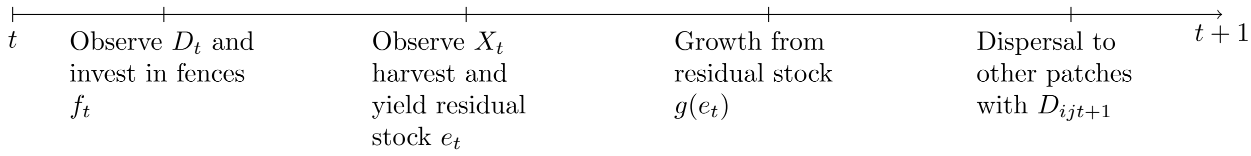

Figure 1: Timing of the model

8.1 Proofs

8.1.1 Proof of proposition 1

Given that $d_{ijt+1}(f_{it}^j, f_{jt}^i) = 0$, taking the first order condition of eq. 5 yields the results in proposition 1.

8.1.2 Proof of proposition 2

Using the fact that $d_{iit+1} = 1 - \sum_{j\neq i} d_{ijt+1}(f_{it}^j, f_{jt}^i)$, the first order conditions can be rewritten :

$$\begin{aligned}
&\frac{\partial V}{\partial e_{it}} = 0 \\
\iff & -c_i(e_{it}) + k_i(e_{it}) + \delta\left(d_{iit+1}g_i'(e_{it})c_i(X_{it+1}) + \sum_{j\neq i} d_{ijt+1}(f_{it}^j, f_{jt}^i)g_i'(e_{it})c_j(X_{jt+1})\right) = 0 \\
\iff & -c_i(e_{it}) + k_i(e_{it}) + \delta\left(\left(1 - \sum_{j\neq i} d_{ijt+1}(f_{it}^j, f_{jt}^i)\right) g_i'(e_{it})c_i(X_{it+1}) + \sum_{j\neq i} d_{ijt+1}(f_{it}^j, f_{jt}^i)g_i'(e_{it})c_j(X_{jt+1})\right) = 0 \\
\iff & k_i(e_{it}) = c_i(e_{it}) - \delta g_i'(e_{it})\left[c_i(X_{it+1}) + \sum_{j\neq i}^{N} d_{ijt+1}(f_{it}^j, f_{jt}^i)(c_j(X_{jt+1}) - c_i(X_{it+1}))\right]
\end{aligned}$$

And for fencing, using Leibniz rule for integral differentiation yields :

$$\begin{aligned}
&\frac{\partial V}{\partial f_{it}^j} = 0 \\
\iff & \delta\left(-\frac{\partial d_{ijt+1}(f_{it}^j, f_{jt}^i)}{\partial f_{it}^j} g_i(e_{it} + \frac{\partial d_{jit+1}(f_{jt}^i, f_{it}^j)}{\partial f_{it}^j} g_j(e_{jt})\right) c_i(X_{it+1}) \\
& + \delta\left(-\frac{\partial d_{jit+1}(f_{jt}^i, f_{it}^j)}{\partial f_{it}^j} g_j(e_{jt}) + \frac{\partial d_{ijt+1}(f_{it}^j, f_{jt}^i)}{\partial f_{it}^j} g_i(e_{it})\right) c_j(X_{jt+1}) + \gamma_i^j(f_{it}^j) = 0 \\
\iff & \delta\big(c_i(X_{it+1}) - c_j(X_{jt+1})\big)\left(\frac{\partial d_{ij+1}}{\partial f_{it}^j} g_i(e_{it}) - \frac{\partial d_{jit+1}}{\partial f_{it}^j} g_j(e_{jt})\right) = \gamma_i^j(f_{it}^j)
\end{aligned}$$

8.1.3 Proof of proposition 3

Using proposition 2, and inputing $c_j(s) = c_i(s) = c$:

$$\begin{aligned}
& k_i(e_{it}) = c - \delta g_i'(e_{it})\left[c + \sum_{j\neq i}^{N} d_{ijt+1}(f_{it}^j, f_{jt}^i)(c - c)\right] \\
\Rightarrow & k_i(e_{it}) = c - \delta g_i'(e_{it})c
\end{aligned}$$

And :

$$
\begin{aligned}
&\delta\big(c_i(X_{it+1}) - c_j(X_{jt+1})\big)\left(\frac{\partial d_{ij+1}}{\partial f_{it}^j} g_i(e_{it}) - \frac{\partial d_{jit+1}}{\partial f_{it}^j} g_j(e_{jt})\right) = +\gamma_i^j(f_{it}^j) \\
\Rightarrow &\delta\big(c - c\big)\left(\frac{\partial d_{ij+1}}{\partial f_{it}^j} g_i(e_{it}) - \frac{\partial d_{jit+1}}{\partial f_{it}^j} g_j(e_{jt})\right) = \gamma_i^j(f_{it}^j) \\
\Rightarrow &0 = \gamma_i^j(f_{it}^j) \Rightarrow \forall j, f_{it}^j = 0
\end{aligned}
$$

8.1.4 Proof of proposition 4

In patch A, given $c_B(s) < c_A(s)$:

$$
\begin{aligned}
&\delta\big(c_A(X_{At+1}) - c_B(X_{Bt+1})\big)\left(\frac{\partial d_{ABt+1}}{\partial f_{At}^B} g_A(e_{At}) - \frac{\partial d_{BAt+1}}{\partial f_{At}^B} g_B(e_{Bt})\right) = \gamma_A\left(f_{At}^B\right) \\
\Rightarrow &\delta\big(c_A(X_{At+1}) - c_B(X_{Bt+1})\big)\left(-\frac{\partial d_{BAt+1}}{\partial f_{At}^B} g_B(e_{Bt})\right) = 0 \\
\Rightarrow &f_{At}^B \to \infty \Rightarrow d_{BAt+1} = 0
\end{aligned}
$$

In patch j:

$$
\begin{aligned}
&\delta\big(c_B(X_{Bt+1}) - c_A(X_{At+1})\big)\left(\frac{\partial d_{BAt+1}}{\partial f_{Bt}^A} g_B(e_{Bt}) - \frac{\partial d_{ABt+1}}{\partial f_{Bt}^A} g_A(e_{At})\right) = 0 \\
\Rightarrow &\delta\big(c_B(X_{Bt+1}) - c_A(X_{At+1})\big)\left(-\frac{\partial d_{ABt+1}}{\partial f_{Bt}^A} g_A(e_{At})\right) < 0 \\
\Rightarrow &f_{Bt}^A = 0 \Rightarrow d_{ABt+1} = 1
\end{aligned}
$$

And replace those values in equations 8 and 9 with $\gamma_i(\cdot) = 0$.

8.1.5 Proof of proposition 5

Intuition is clear, but proof with :

- Differentiation of both FOCs
- Cramer Rule

8.1.6 Proof of proposition 6

8.1.7 Proof of proposition 7

8.1.8 Proof of proposition 8

The sole owner minimizes $C_i(e_{it}, X_{it}, f_{it}^1, ..., f_{it}^N) + \delta C_i(e_{it+1}, X_{it+1}, f_{it+1}^1, ..., f_{it}^N)$. First order conditions yield :

$$
\begin{cases}
k_i(e_{it}) = c_i(e_{it}) - \delta g_i'(e_{it}) c_i(X_{it+1})\left[1 - \sum_{j\neq i} d_{ijt+1}(f_{it}^j, f_{jt}^i)\right] \\
\\
-\frac{\partial d_{jit+1}}{\partial f_{it}^j}\delta g_j(e_{jt}) c_i(X_{it+1}) = 0
\end{cases}
$$

The second equation implies a dominant strategy, as the marginal net benefits from fencing are independent of other players strategy. Hence, $f_{it}^{j} \to \infty$. As this condition holds $\forall i, j$, then :

$$k_i(e_{it}) = c_i(e_{it}) - \delta g_i'(e_{it}) c_i(X_{it+1})$$

8.1.9 Proof of proposition 9

First order conditions are :

$$\begin{cases} k_i(e_{it}) = c_i(e_{it}) - \delta g_i'(e_{it}) c_i(X_{it+1}) \left[1 - \sum_{j \neq i} d_{ijt+1}(f_{it}^{j}, f_{jt}^{i})\right] \\ \\ -\frac{\partial d_{jit+1}}{\partial f_{it}^{j}} \delta g_j(e_{jt}) c_i(X_{it+1}) = \gamma_i^{j}(f_{it}^{j}) \end{cases} \tag{16}$$

Equation 16 differs from the optimal fencing defined in eq 9, by a factor of $-c_j(X_{jt+1})$, hence resulting in overfencing.

8.1.10 Proof of proposition 10

8.1.11 Proof of proposition 11

8.1.12 Proof of proposition 12

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