Limited-tenure concessions in a patchy system

Abstract

Spatially-allocated concessions with limited-duration ownership are increasingly employed to manage natural resources in many countries, yet they have received little attention from economists. Motivated by settings such as territorial user right fisheries (TURFs), we develop a model to analyze the effects of spatial concessions with limited tenure. The resource migrates around the system and thus induces a spatial externality, so complete decentralization into spatial property rights will not solve the tragedy of the commons. We analyze a system in which concessions can be renewed, but only if their owners maintain resource stocks above a pre-defined target. We show that this instrument improves upon the decentralized property right solution and can replicate (under general conditions) the socially optimal extraction path in every patch, in perpetuity. The duration of tenure and the dispersal of the resource play pivotal roles in whether this instrument achieves the socially optimal outcome, and sustains cooperation of all concessionaires.

Key words: Concessions; cooperation; TURFs; natural resources; spatial externalities; dynamic games

JEL classification: C7; D62; 013; Q20

1 Introduction

Billions of people living all across the planet depend on natural resources such as farmland, fish, and forests, for livelihoods and sustenance.[1] However, property rights failures, among other reasons, may hinder the sustainable use of these resources, which are increasingly overexploited (Baland and Platteau 1997; Irrera et al. 2001). Partly in response to these trends, many countries have adopted policies and reforms to devolve the management of forests, fisheries or irrigation water to states, communities, or individuals in the form of property rights. Among

[1]For instance, according to FAO (2009) the livelihoods of over 500 million people in developing countries depend directly or indirectly on fisheries and aquaculture.

diverse forms of property rights, concessions have been widely adopted to manage forests, gas, and oil around the world. While these resources tend to be relatively immobile,[2] other mobile resources such as fisheries are increasingly managed with spatial property rights (e.g. TURFs) and associated spatial concessions. Managing mobile resources with spatially-delineated concessions raises a potential challenge: When concession contracts are awarded over a fixed geographical area, the resources they are meant to encapsulate may disperse beyond the domain of the concessionaire, which could significantly alter her incentives for sustainable resource use.[3] This mobility implies a spatial externality across concessionaires. This article analyzes and informs the design of concession agreements for managing mobile natural resources. While we are primarily motivated by TURF-like concessions for managing marine resources, the principles derived here apply more broadly to any spatially-managed mobile renewable resource.

We define a ”concession” as any system that grants rights to exploit a natural resource for a fixed duration over a limited area to a concessionaire. This instrument thus provides area-based rights, like any territorial use right system, but the concessionaire effectively becomes the short-term owner and manager of the natural resource in the concession area. Concessions of this form are used in various sectors of the economy, including infrastructure, construction, and, most importantly for our study, extractive natural resources. Despite the widespread use of natural resource concessions, to the best of our knowledge, these contracts do not typically address the challenge of resource mobility. Our paper examines the design of concessions for managing such spatially-connected renewable resources.

Our study is related to a broad literature applying property rights theory to common-pool resource management. This literature has focused on the dichotomy between private (Demsetz 1967; Cheung 1970) vs. common property rights (Ostrom 1990), and on the different instruments available to implement these regimes. Two instruments that emerge are *territorial use rights* (such as TURFs) and *use rights on the resource*. The latter instrument assigns rights to extract a specified quantity of the resource, while the former instrument designs rules of exploitation in a limited area. Territorial use rights thus grant secure rights to parts of a resource (Fischer and Laxminarayan 2010), as in a concession system. While the *spatial* approach is increasingly used to govern natural resources, spatial externalities may occur: harvest in one patch-area inherently affects harvests in other patch-areas (see Kapaun and Quaas (2013) and Costello et al. (2015) for recent contributions). The mobility of natural resources may consequently chal-

[2]Though even oil, gas, and trees can “flow” across jurisdictional boundaries.

[3]For instance the world’s oceans consist of about 200 spatial exclusive property right assignments (the exclusive economic zones) that are traversed by migratory species such as tuna, sharks, and whales (White and Costello 2014).

lenge incentives for efficient resource use.[4] In this paper, we design and analyze a concession system that can be used as a coordination device to overcome the spatial externality problems caused by the mobility of renewable natural resources. This analysis is relevant in developing countries where, for example, TURFs are increasingly used to manage fisheries, including India, Bangladesh, Fiji, Sri Lanka and Vietnam (Jardine and Sanchirico 2012), among many others. In Chile, over 700 TURFs are operational coast-wide (Wilen et al. 2012). And on the Pacific coast of Baja California, Mexico, TURFs are granted to several cooperatives for a 20 year duration with the possibility of renewal.

Following seminal contributions (Grossman and Hart 1986; Hart and Moore 1990) the literature on property rights has received renewed attention, mainly in organizational economics, and the analysis of property rights has been developed with a focus on issues raised by incentive structures (Kim and Mahoney 1967). This literature puts some focus on conditional (or contingent) property rights, which are allocated *ex ante*, for instance before a good is produced, and materialize only if certain conditions are fulfilled (Maskin and Tirole 1999; Werlin 2003). This is typically the case of a concession granted conditionally on the concessionaire's pattern of future resource extraction. Many contracts belong to this category: Guarantee or fire-insurance contracts are examples of contingent property rights. Optimal contracts with conditional payoffs are other examples: payments may for instance be conditional on the outcome of political processes (Musto and Yilmaz 2003; Engelhardt and Svec 2016).[5] More closely related to our paper, property rights theory is applied to strategic management such as oil field unitization (Kim and Mahoney 1967; Libecap and Wiggins 1985), a private contractual arrangement aimed at reducing externalities from a migratory common-pool resource with important contracting specifications (such as duration and economic sharing rules). Consistently with this type of arrangement, we thus design a concession contract stipulating conditions that define the renewal process.

This paper is also related to the literature focusing on specific features of con-

[4]The mismatch between the scale of property rights and the scale of the resource is emphasized by many authors as a potential limitation (White and Costello 2011; Nguyen Thi Quynh et al. 2017; Aburto-Oropeza et al. 2017).

[5]Conditional payment schemes, such as payments for environmental services, may be implemented in case of successful spatial coordination (Banerjee et al. 2017) or provided a specific ecological outcome is achieved, for instance, the survival of an endangered species (Drechsler 2017). As in such schemes, conditionality is an important feature of our concession instrument. Moreover, the appropriate design of such schemes and of our instrument raises issues such as the length of the contract (Drechsler et al. 2017) or the tenure duration. Yet PES are very different instruments from the one proposed here: they are monetary instruments, while our proposed system is non-monetary. In situations where common-property resources are regulated at the national or local scale, a non-monetary instrument may be more feasible when governments have tight budget restrictions, as is the case in many developing countries.

cession contracts such as the design of concession agreements (Dasgupta et al. 1999; Leffler and Rucker 1991), the awarding process (Klein 1998), the choice of royalties (or fees) for extraction rights (Giudice et al. 2012), and issues of imperfect enforcement (Guasch et al. 2004). Concessions design features have been analyzed in natural resource settings such as oil, gas, minerals, forests, and fisheries (Manh Hung et al. 2006; Jardine and Sanchirico 2012). Prominently, the concession agreement was nearly the exclusive form of petroleum contract between host governments of developing countries and international extraction companies until 1950 (Machmud 2000). In a generic setting without spatial externalities, Costello and Kaffine (2008) focus on the efficiency of this system. They find that limiting tenure weakens the incentive to steward one's own resource, but that fully efficient extraction may still be possible.

We focus attention on the design of concessions to efficiently manage a spatially-connected resource in which spatial externalities generate a market failure. To do so, we must account for spatial and temporal resource dynamics, as well as the incentives of interconnected property owners. Our analysis is designed to provide general insights about spatial concessions, but is focused on contributing to key contemporary policy questions. We begin by developing a model of spatial economic behavior among a set of spatially-distinct resource patches, taking as given that resources can be mobile. We then consider three different management regimes: (i) the socially optimal regime, (ii) the decentralized regime and (iii) the concession regime. In the last regime, the instrument we propose involves assigning limited-duration tenure of each patch to a private concessionaire, with possible renewal under certain conditions. Under this instrument, the regulator announces for each patch a "minimum stock," below which the concessionaire should never harvest. This is a stylized version of how many concessions are implemented in practice.[6] Under this set of spatial concessions with limited tenure, each concessionaire then faces an interesting, and to our knowledge unexplored, set of incentives: The concessionaire must decide whether to comply with the minimum stock requirement or to defect, given her payoff will depend on the strategy adopted by others. On one hand, adhering to the minimum stock requirement guarantees renewal, and thus raises future payoffs. On the other hand, mining the stock (and

[6]For example, the TURF systems in Mexico and Chile contain maximum harvest provisions, whose adherence is required for renewal. Moreover, as explained in Jarvis and Wilen (2016) in the case of Chile, in order for the government to determine a well-designed total allowable catch (TAC) for each TURF, a mandatory annual stock assessment has to be carried out by technical consultants approved by the government and paid by TURF members. This suggests that regular and proper stock assessment is a mandatory part of a well-designed concession system. This is further supported by Hilborn et al. (2005), who explain that successful concession systems based on harvest levels tend to engage in active research programs funding stock assessments directly, and by Wilen et al. (2012), who provide another example of successful TURF initiatives in Japan, where scientific advice regarding stock assessment is provided to define sustainable TACs.

thus driving it below the minimum stock requirement) returns large payoffs in the current concession period.

Despite the complexity of this setup, we are able to derive explicit, analytically tractable results with concrete policy implications. First, we derive the optimal defection strategy for any single concessionaire, and use it to derive a set of conditions under which cooperation can emerge as an equilibrium outcome and gauge whether this leads to fully efficient resource use. We then focus in on the properties of the system that ensure cooperation (or conversely, ensure defection). We notably show that the decision of cooperation depends critically on resource mobility (e.g. whether the concession area is a source or a sink). We then find an interesting, and somewhat counterintuitive result. We show that longer tenure is more likely to lead to defection from the efficient harvest rate. This odd result is of great importance for policy design, since length is a critical issue for a concession regime to be successful. Furthermore, it seems to contradict the economic intuition that more secure property rights (here, the longer the duration of tenure) give rise to more efficient resource use. For instance, Boscolo and Vincent (2000) provide a numerical analysis of forest concessions to examine how tenure length and performance-based renewal might affect logging incentives. They conclude that discounting tends to mediate the effects of tenure length, but that the promise of renewal can motivate responsible behavior. Costello and Kaffine (2008) show that any tenure length is sufficient to induce the optimal resource use, on the condition that the probability of renewal is sufficiently high. In our paper, a long tenure period implies that the regulator essentially loses the ability to manipulate a concessionaire's harvest incentives via the promise of tenure renewal. And, we can show that for sufficiently long (but still finite) tenure length, concessionaires will always have incentives to defect; thus tenure must not be too long.

The paper is structured as follows: In the next section we set up the model and characterize concessionaires' incentives under various property right regimes. In Section 3 we highlight the conditions for cooperation with an emphasis on spatial characteristics of the model and the tenure length. A discussion on the robustness of the instrument is provided in Section 4. Section 6 summarizes and concludes the paper. Most technical proofs are provided in an Appendix.

2 Model & strategies

We begin by introducing a spatial model of natural resource exploitation with spatially-connected property owners. We then home-in on the incentives for different harvest strategies corresponding to three property right regimes: the social planner's spatially-optimized benchmark, the decentralized perpetual property right holders, and the case of decentralized limited-tenure concessions. Versions of the social planner's benchmark and the case of perpetual property right holders have been analyzed in Costello and Polasky (2008) and in Kaffine and Costello (2011), which is why we only briefly state the corresponding properties. The last case introduces the instrument on which we focus.

2.1 The model

We follow the basic setup of Kaffine and Costello (2011) and Costello et al. (2015) where a natural resource stock is distributed heterogeneously across a discrete spatial domain consisting of N patches. Patches may be heterogeneous in size, shape, economic, and environmental characteristics, and resource extraction can occur in each patch. Using a discrete-time model, the stock residing in property i at the beginning of time period t is given by x_{it}, and harvests undertaken in that property, h_{it}, will reduce the stock over the course of that time period: Thus leaves a "residual stock" at the end of the period of $e_{it} \equiv x_{it} - h_{it}$. The residual stock may grow, and the growth conditions may be patch-specific denoted by the parameter α_j. Finally, as the resource is mobile and can migrate around this system, we follow the recent literature from the natural sciences (see, e.g., Nathan et al. (2002), or Siegel et al. (2003)) who denote dispersion by $D_{ij} \geq 0$ the fraction of the resource stock in patch i that migrates to patch j in a single time period.[7] Since some fraction of the resource may indeed flow out of the system entirely, the dispersal fractions need not sum to one: $\sum_i D_{ji} \leq 1$. Assimilating all of this information, the equation of motion in patch i is given as follows:

$$x_{it+1} = \sum_{j=1}^{N} D_{ji} g(e_{jt}, \alpha_j). \tag{1}$$

Here $g(e_{jt}, \alpha_j)$ is the period-t production in patch j. Following the literature, we require that $\frac{\partial g(e,\alpha)}{\partial x} > 0$, $\frac{\partial g(e,\alpha)}{\partial \alpha} > 0$, $\frac{\partial^2 g(e,\alpha)}{\partial e^2} < 0$, and $\frac{\partial^2 g(e,\alpha)}{\partial e \partial \alpha} > 0$. We also assume that extinction is absorbing, $g(0;\alpha_j) = 0$, and that the growth rate is finite, $\frac{\partial g(e,\alpha)}{\partial e}|_{e=0} < \infty$.[8] All standard biological production functions are special cases of $g(e,\alpha)$.

[7] This model assumes density-independent dispersal parameters, D_{ij}. By doing so we follow a large part of the literature on metapopulation and source-sink dynamics (Doak 1995; Levin 1974; Sanchirico and Wilen 2009; Wootton and Bell 1992). This allows us to analyze the comparative statics effect of dispersal on cooperation vs. defection incentives. Dispersal may be influenced by factors like ocean currents, or population size in an area, among others. Dependence on local population abundance does not qualitatively affect our main results, but impedes on the model tractability.

[8] We will omit the growth-related parameter in most of what follows, except briefly before Section 3.2 and in Section 3.3, where the effect of this parameter will be analyzed. Thus, we will use the notation $g_i'(e)$ and $g_i''(e)$ instead of (respectively) $\frac{\partial g(e,\alpha_i)}{\partial e}$ and $\frac{\partial^2 g(e,\alpha_i)}{\partial e^2}$ in most parts of the paper.

We assume that both price and marginal harvest cost are constant in a patch, though they can differ across patches. The resulting *net price* is given by p_i.[9] The current profit from harvesting $h_{it} \equiv x_{it} - e_{it}$ in patch i at time t is:

$$\Pi_{it} = p_i \left(x_{it} - e_{it} \right). \tag{2}$$

We will employ this framework to compare the outcome and welfare implications of three alternative property right systems.

At this stage it is important to make the following observation. Real world natural resource management is more complex than the setting depicted here. For instance, there could be more complicated cost structures. We have proposed a relatively simple, analytically tractable model to gain insights on the potential performance of a spatial concession instrument, while keeping the most relevant features when studying issues of performance. This model still allows for dynamic and spatial externalities, in addition to strategic behavior between patch owners. It allows us to gain sharp insights on the effects of ecological and economic fundamentals and of features of the instrument (e.g. tenure length and target stock requirements) on its performance. By exploiting the structure of our dynamic and spatial game, we will be able to obtain sharp analytical results. We will derive closed form expressions of the owners' optimal payoffs when committing to the concession instrument, and when following their best defection strategies. This is necessary to analytically assess the performance of the instrument. Moreover, we formally analyze the robustness of our results when costs are stock-dependent in Section 4.2.

2.1.1 Social Planner's Problem

As a useful benchmark, we begin with the social planner who seeks to maximize the net present value of profit across the entire domain given the discount factor δ. The planner's objective is:

$$\max_{\{e_{1t},...,e_{Nt}\}} \sum_{t=0}^{\infty} \sum_{i=1}^{N} \delta^t p_i \left(x_{it} - e_{it} \right), \tag{3}$$

subject to the spatial equation of motion (1) for each patch $i = 1, 2, ..., N$. Focusing on interior solutions,[10] in any patch i, the planner should achieve a residual stock level as follows:

$$g_i' \left(e_{it}^* \right) = \frac{p_i}{\delta \sum_j D_{ij} p_j} \tag{4}$$

[9] This assumption is common and is consistent with the case where the market price is the same in all patches, while marginal costs might be patch-specific (due to geographical locations, different costs of access).

[10] The case of interior socially optimal policies is consistent with sustainable management of the resource. It allows us to emphasize the importance of ecological and economic fundamentals on

The optimal residual stock results from the standard trade-off between the present profits from harvest and the discounted sum of future benefits given growth and dispersal to all patches. Note, by inspection, that these optimal residual stock levels are time and state independent. This implies that each patch has a single optimal residual stock level that should be achieved every period into perpetuity satisfying, for any period t:

$$e^*_{it} = e^*_i. \tag{5}$$

Since biological growth, dispersal, and economic returns are patch-specific, the optimal policy will vary across patches. Equation 4 highlights immediately that the optimal policy depends on patch-specific net prices, growth, and dispersal and self-retention parameters.

2.1.2 Decentralized Perpetual Property Right Holders

The second regime is the case in which each patch is owned in perpetuity by a single owner who seeks to maximize the net economic value of harvest from his patch, with complete information about the stock, growth characteristics, and economic conditions present throughout the system. In that case owner i solves:

$$\max_{\{e_{it}\}} \sum_{t=0}^{\infty} \delta^t p_i \left(x_{it} - e_{it}\right). \tag{6}$$

subject to the equation of motion (1). Following Lemma 1 in Kaffine and Costello (2011), at the subgame perfect Nash equilibrium owner i will always harvest down to a residual stock level $\bar{e}_{it}$ that satisfies:[11]

$$g_i'(\bar{e}_{it}) = \frac{1}{\delta D_{ii}}. \tag{7}$$

The owner takes as given the behavior of other owners and realizes that he will not be the residual claimant of any conservative harvesting behavior. Thus, he behaves as if any additional resource that disperses out of his patch will be lost (indeed it will be harvested by his competitors). This is why the only dispersal term to enter

the performance of the instrument. Technically, this is equivalent to assuming $g_i'(0) > \frac{p_i}{\delta \sum_j D_{ij} p_j}$ and $x_{i0} > (g_i')^{-1}\left(\frac{p_i}{\delta \sum_j D_{ij} p_j}\right)$. The polar case where social efficiency would require $e^*_{it} = 0$ $\forall t \geq 0$ in some patches can be addressed by our instrument. Indeed, if marginal incentives at the first best correspond to this case for some patches, then the marginal incentives of these patches' owners in the decentralized situation correspond to this case too. The other polar case, where $e^*_{it} = x_{it}$ $\forall t \geq 0$ for at least one patch i, cannot be addressed by our instrument (or by any concession instrument), this would require combining it with a side-payment scheme.

[11]Required necessary conditions are $g_i'(0) > \frac{1}{\delta D_{ii}}$ and $x_{i0} > (g_i')^{-1}\left(\frac{1}{\delta D_{ii}}\right)$.

the optimal residual stock term is D_{ii}, the fraction of the resource that remains in his patch. It is straightforward to show that $\bar{e}_{it} \leq e^*_{it}$ (with strict inequality as long as $D_{ii} \neq 1$), and thus that achieving social efficiency in a spatially connected system will require some kind of intervention or cooperation. Moreover, Equation (7) implies that $\bar{e}_{it} = \bar{e}_i$ for any time period.[12]

2.1.3 Decentralized, Limited-Tenure Property Rights

In the final regime, and the one on which we focus in this paper, we assume that ownership over patch i is granted to a private concessionaire for a duration of T periods, to which we will refer as the "tenure block" for the spatial concession. All concessionaires have the possibility of renewal provided that certain conditions are met. Indeed, it is the possibility of renewal that will ultimately incentivize the concessionaire to deviate from her (excessively high) privately-optimal harvest rate; we will leverage this fact to design spatial concession contracts to induce efficient outcomes.[13]

We begin by defining an arbitrary set of instrument parameters, and we then evaluate the manner in which each concessionaire would respond to that set of incentives. The general instrument is defined as follows:

Definition 1. *The* Limited-Tenure Spatial Concession Instrument *is defined by a "target stock," $\mathcal{S}_i$, and a tenure period, $\mathcal{T}_i$.*

The regulator imposes only a single rule on the concessionaire: At the end of the tenure block (i.e. at time $\mathcal{T}_i - 1$, since the block starts at $t = 0$), the concession will be renewed (under terms identical to those of the first tenure block) if and only if the resource stock is maintained at or above the target stock in every period. Because $e_{it} \leq x_{it}$, this rule implies that concession i will be renewed if and only if:

$$e_{it} \geq \mathcal{S}_i \qquad \forall t \leq \mathcal{T}_i - 1. \tag{8}$$

Note that we allow for this instrument to be explicitly spatial in the sense that $\mathcal{S}_i \neq \mathcal{S}_j$.

Beyond the assignment of the concession the regulator plays no role in the management of the resource; all harvest decisions are made privately. Because the regulator would like to replicate the social planner's solution (see Section 2.1.1), she must determine a set of target stocks $\{\mathcal{S}_1, \mathcal{S}_2, ..., \mathcal{S}_N\}$ and tenure lengths $\{\mathcal{T}_1, \mathcal{T}_2, ...\mathcal{T}_N\}$ (i.e., a $\{\mathcal{S}_i, \mathcal{T}_i\}$ pair to offer each concessionaire) that will incentivize

[12] As shown in Kaffine and Costello (2011), this result actually implies that the open loop and feedback control rules are identical.

[13] We focus on the spatial externalities driven by resource mobility, though the conditional renewal instrument we study may also be modified to address other types of externalities.

all concessionaires to simultaneously, and in every period, deliver the socially optimal level of harvest in all patches. In practice, we will restrict attention to tenure lengths that are the same for all concessionaires, so $\mathcal{T}_i = T$, $\forall i$.[14]

The focus of our study is to show that, if designed properly, spatial limited-tenure concessions can be used to induce concessionaires to manage resources in a socially optimal manner. Agents may, or may not, comply with the terms of the concession contract. If all N concessionaires choose to comply with the target stocks in every period of every tenure block, we refer to this as *cooperation.* All owners will then earn an income stream in perpetuity. Instead, if a particular owner i fails to meet the target stock requirement (i.e, in some period she harvests the stock below $\mathcal{S}_i$), then, while she will retain ownership for the remainder of her tenure block (and thus be able to choose any harvest over that period), she will certainly not have her tenure renewed. In that case, owner i's payoff will be zero every period after her current tenure block expires. Thus, the instrument raises a trade-off for each concessionaire who has to choose between cooperation and defection. In the following, since an owner's payoff depends on others' actions, we assume that if concessionaire i defects, then the concession is granted to a new concessionaire in the subsequent tenure block. If all initial owners decide to defect and are not renewed at the end of the current tenure, then the game ends.[15]

2.2 Cooperation vs. Defection

We now characterize the payoffs that each concessionaire could achieve under cooperation and under defection, and we characterize the optimal defection strategies by any concessionaire.

We first consider the case where all N concessionaires cooperate and thus comply with the target stocks in every period of every tenure block. Provided they do not exceed the target stock (so they do not over-comply), then concessionaire i's present value payoff is:

$$\Pi_i^c = p_i \left[x_{i0} - \mathcal{S}_i + \sum_{t=1}^{\infty} \delta^t \left(x_i^* - \mathcal{S}_i \right) \right]. \tag{9}$$

where x_{i0} is the (given) starting stock and $x_i^* = \sum_j D_{ji} g(\mathcal{S}_j)$.

[14]Intuitively, since concessionaires are heterogeneous, tenure lengths could be heterogeneous as well. In order to limit the complexity of the scheme, and because the use of a uniform tenure length for renewal seems to be the norm for real-world cases of concessions-regulated resources, we consider the longest tenure that is compatible with all concessionaires' incentives to cooperate. This characterization is provided by expression 14 in Section 3.

[15]This rule turns out to be irrelevant because, as we late show, if everyone defects, the natural resource is driven extinct.

Let us now turn to the characterization of the optimal defection strategies pursued by concessionaires. Assume that concessionaire i defects during an arbitrary tenure block k, given all concessionaires, except i, follow their cooperation strategies (that is, they are unconditional cooperators), the optimal defection strategy of concessionaire i is characterized in the following result.[16]

Proposition 1. *1. First assume that* $\frac{p_i}{\delta \sum_j D_{ij} p_j} < g_i'(0) \leq \frac{1}{\delta D_{ii}}$. *Then the optimal defection strategy of concessionaire* i *in tenure block* k *is given by* $\bar{e}_{it} = 0$ *for any period* $(k-1)T \leq t \leq kT - 1$.

2. Second, assume that $g_i'(0) > \frac{1}{\delta D_{ii}}$. *Then the optimal defection strategy of concessionaire* i *in tenure block* k *is characterized as follows:*

$$\bar{e}_{ikT-1} = 0$$

and, for any period $(k-1)T \leq t \leq kT - 2$, *we have* $\bar{e}_{it} = \bar{e}_i > 0$ *where:*

$$g_i'(\bar{e}_i) = \frac{1}{\delta D_{ii}} \quad \text{with } \bar{x}_i > \bar{e}_i.$$

When marginal growth of the resource $g_i'(0)$ is sufficiently low in area i, Proposition 1 states that a concessionaire who decides to defect *sometime* during tenure block k, will decide to completely mine the resource in his patch at every period of the tenure block. By contrast, when marginal growth is high enough, this defecting concessionaire will (1) choose the non-cooperative level of harvest (see Section 2.1.2) up until the final period of the tenure block and (2) then completely mine the resource, leaving nothing for the subsequent concessionaire.[17] Either way, the resource is completely mined in that patch by the end of the tenure block. Note that the optimal defection strategy does not depend on the tenure block, k.[18] The finding that the defection strategy is independent of the tenure block greatly simplifies the characterization of equilibrium strategies. The present value of owner i's defection payoffs is:

$$\Pi_i^d = p_i \left[x_{i0} - \mathcal{S}_i + \sum_{t=1}^{(k-1)T-1} \delta^t \left(x_i^* - \mathcal{S}_i \right) + \delta^{(k-1)T} \left(x_i^* - \bar{e}_i \right) + \sum_{t=(k-1)T+1}^{kT-2} \delta^t \left(\bar{x}_i - \bar{e}_i \right) + \delta^{kT-1} \bar{x}_i \right]. \tag{10}$$

[16] The proof relies on backward induction arguments since defection would occur on one tenure block, and the defecting agent would not be renewed again.

[17] Note that if only one concessionaire defects, the entire stock will not be driven extinct because patch i can be restocked via dispersal from patches with owners who cooperated.

[18] Regarding the block in which defection occurs, patch owner i's optimal defection strategy in period t is independent of period t choices by other patch owners, and patch owner i's optimal defection in period $t+1$ is independent of choices made by any owner prior to period t.

where $\bar{x}_i = D_{ii} g(\bar{e}_i) + \sum_{j \neq i} D_{ji} g(\mathcal{S}_j)$.

Thus, the payoff when patch owner i defects during tenure block k is given by (1) the profit obtained while abiding by the target stock prior to the k^{th} tenure block, and (2) the profit from non-cooperative harvesting during tenure block k, until finally extracting all the stock in the final period of the k^{th} tenure block, $kT-1$. We will make extensive use of the defection strategy in what follows. We next turn to the conditions that give rise to cooperation.

3 Conditions for Cooperation

Here we derive the conditions under which all N concessionaires willingly choose to cooperate in perpetuity. We will proceed in three steps. First, we derive the target stocks that must be announced $(\mathcal{S}_1, ..., \mathcal{S}_N)$ by the regulator who wishes to replicate the socially optimal level of extraction in every patch at every time, and we derive necessary and sufficient conditions for cooperation to be sustained. Second we discuss the effects of the patch-level parameters. Finally, we will assess the influence of the tenure duration T on the emergence of cooperation, and provide comparative statics results.

3.1 The emergence of cooperation

Our interest here is to design the spatial concession instrument to replicate the socially-optimal harvest in each patch at every time. Given that goal, we first prove that the regulator *must* announce, as a patch-i target stock, the socially-optimal residual stock for that patch.

Lemma 1. *A necessary condition for social optimality is that the regulator announces as target stocks: $\mathcal{S}_1 = e_1^*$, $\mathcal{S}_2 = e_2^*$,..., $\mathcal{S}_N = e_N^*$, where e_i^* is given in Equation 4.*

The proof for Lemma 1 makes use of two main results from above. First, because $\bar{e}_i \leq e_i^*$, if the regulator announces any $\mathcal{S}_i < e_i^*$, then the concessionaire will find it optimal to drive the stock below e_i^*, which is not socially optimal. Second, if the regulator sets a high target, so $\mathcal{S}_i > e_i^*$, then the concessionaire will either comply with the target (in which case the stock is inefficiently high) or will defect and reach an inefficiently low target stock. Either way, this is not socially optimal, so Lemma 1 provides the target stocks that must be announced.

Thus, we can restrict attention to the target stocks $\mathcal{S}_i = e_i^*\ \forall i$. In that case, compliance by concessionaire i requires that $e_{it} \geq e_i^*\ \forall t$, so she must never harvest below that level. Our next result establishes that, while concessionaire i is free to choose a residual stock that *exceeds* e_i^*, she will never do so.

Proposition 2. *If concessionaire i chooses to cooperate, she will do so by setting $e_{it} = e_i^* \ \forall i, t$.*

Proposition 2 establishes that, if it can be achieved, cooperation will involve each concessionaire leaving precisely the socially-optimal residual stock in each period.

To analyze the conditions under which cooperation may emerge as a non cooperative outcome, we proceed as follows. We characterize the conditions ensuring that any given concessionaire (say, $i \in I$) does not have incentives to defect from the strategy characterized by Proposition 2 when all other concessionaires follow this strategy. In any given tenure block, the basic decision facing concessionaire i is whether or not to comply with the target stock requirement in each period. When all other concessionaires follow the strategy characterized by Proposition 2, one simply calculates her payoff from the optimal defection strategy (characterized by Proposition 1) and compares it to her payoff from the cooperation strategy. We define concessionaire i's *willingness-to-cooperate* by:

$$W_i \equiv \Pi_i^c - \Pi_i^d. \tag{11}$$

Each concessionaire must trade off between a *mining* effect, in which she achieves high short-run payoffs from defection during the current tenure block, and a *renewal* effect, in which she abides by the regulator's announced target stock, and thus receives lower short-run payoff, but ensures renewal in perpetuity. This comparison turns out to have the following straightforward representation:

Proposition 3. *Complete cooperation emerges as an equilibrium outcome if and only if, for any concessionaire i, the following condition holds:*

$$\delta x_i^* - e_i^* > \left(1 - \delta^{T-1}\right)\left(\delta \bar{x}_i - \bar{e}_i\right). \tag{12}$$

Proposition 3 shows that the gains from cooperation to concessionaire i ($\delta x_i^* - e_i^*$) must be sufficiently large compared to those corresponding to defection ($\delta \bar{x}_i - \bar{e}_i$). In such cases, we get full cooperation forever.[19] Note that this is possible, e.g. consider the case when agents are patient, and thus the discount factor, δ, is high. Then the right-hand side of Condition 12 gets close to zero, and the left-hand side to $x_i^* - e_i^*$, so as long as we have an interior solution to the optimal spatial problem, the condition holds. On the contrary, when the discount factor gets close to zero, keeping in mind that $e_i^* > \bar{e}_i$, cooperation never arises. These cases are used just as an example: there are cases (depending on spatial parameters) where Condition (12) will hold generically without relying on the assumption of sufficiently patient concessionaires.

[19] The proof of Proposition 1 highlights that defection entails at least some harvest (the stock satisfies $\bar{x}_i = \sum_{j \neq i} D_{ji} g(e_j^*) + D_{ii} g(\bar{e}_i) > \bar{e}_i$). Thus, there are no corner solutions.

We have shown that the instrument we propose can lead to efficient harvesting behavior across space and time in perpetuity. But this relied on a relatively strict enforcement system (an owner who decides to defect is not renewed). Because the welfare gains from cooperation vs. non-cooperation are potentially large, it is possible that less stringent systems would also lead to efficient behavior. Yet, the renewal process adopted here is consistent with the main characteristics of real-world cases of concessions-regulated resources. For instance, the Pacific Norte cooperatives in Baja California Sur (Mexico) were granted 20-year, renewable fishery concessions for abalone and lobster in the 1990s. In a sense, our analysis highlights that, even without accounting for additional incentives (e.g. financial penalties), spatial limited-tenure concessions have attractive appeal.[20]

3.2 Effects of Patch-Level Characteristics

Naturally, patch-level characteristics such as price, growth rates, and dispersal will affect a concessionaire's payoffs and may therefore play a role in the decision of whether to defect or cooperate. The fact that patch-level characteristics may also affect the announced target stocks further complicates the analysis. We next examine the effects of price, growth, and dispersal on the concessionaire i's *willingness-to-cooperate*, defined by Condition (11). Naturally, as a parameter changes, we must trace its effects through the entire system, including how it alters others' decisions. Assuming that the willingness to cooperate is initially positive, the impact of economic parameters, $\{p_i, p_j\}$ is as follows: Concessionaire i's willingness-to-cooperate, W_i, is increasing in its own economic parameter, p_i, but is ambiguous in the net price of the adjacent area, p_j, and depends on the degree of the connection between patches.

The effect of productivity of connected patches is also nuanced. Agent i will be more likely to cooperate with a higher growth rate of the adjacent property, α_j. Since defection implies harvesting one's entire stock, there is little opportunity (under defection) to take advantage of one's neighbor's high productivity. But under cooperation, a larger α_j implies larger immigration, which translates into higher profit. The impact of the growth rate of its own property is ambiguous, α_i. Nevertheless, this impact is negative when the self-retention rate, D_{ii}, is small, while it becomes positive for sufficiently large value. In the former case, the direct impact on the residual stock in patch i offsets all other impacts, but as a small proportion of the resource stay in that area, this decreases the gains from

[20] The use of financial penalties may be infeasible in developing countries, as financial constraints may be tight. From a general point of view, as the effect of financial capacity on natural resource management may be ambiguous (see for instance Tarui (2007) for an analysis of the effect of improved access to credit), relying on the spatial concession instrument avoids potential problems related to the use of monetary devices.

cooperation.

Finally, the effect of spatial parameters leads to interesting conclusions. We provide cases in the Appendix where the cooperation decision is increasing in self-retention rate, D_{ii}, but the impact of this parameter is quite ambiguous since it affects the resource stock under defection and cooperation. On the contrary, concessionaire i's willingness-to-cooperate, W_i, is increasing in D_{ji} in a similar logic as the effect of α_j. In contrast, consider the effect of a higher emigration rate (D_{ij}). It turns out that this reduces the incentive to cooperate. The intuition is that defection incentives are not altered much (since concessionaire i harvests the entire stock under defection), but cooperation incentives are reduced because the regulator will instruct concessionaire i to reduce her harvest under a larger D_{ij}.

Table 1 summarizes these conclusions: their proofs are provided in the Appendix (Section A).

Table 1: Effect of patch-specific parameters on willingness-to-cooperate.

θ	p_i	p_j	α_i	α_j	D_{ii}	D_{ij}	D_{ji}
$\frac{\partial W_i}{\partial \theta}$	$+$	$+/-$	$+/-$	$+$	$+/-$	$-$	$+$

The results above provide insight about how the strength of the cooperation incentive for i depends on parameters of the problem. But whether this incentive is sufficiently strong to induce cooperation (i.e. whether $W_i > 0$) remains to be seen. We focus on resource dispersal, which plays a pivotal role in our story. If the resource was immobile, the patches would not be interconnected, so no externality would exist and private property owners with secure property rights would harvest at a socially optimal level in perpetuity. It is dispersal that undermines this outcome and induces a spatial externality which leads to overexploitation and motivates the need for regulation. Naturally, then, the nature and degree of dispersal will play an important role in the cooperation decisions of each concessionaire.

In this model, dispersal is completely characterized by the NxN matrix whose rows sum to something less than or equal to 1 ($\sum_j D_{ij} \leq 1$). Thus, in theory, there are N^2 free parameters that describe dispersal, so at first glance it seems difficult to get general traction on how dispersal affects cooperation. But Proposition 1 provides a useful insight: *If* concessionaire i decides to defect, she will optimally do so by considering only D_{ii}, thus totally ignoring all other $N^2 - 1$ elements of the dispersal matrix. This insight allows us first to assess the effect of spatial parameters on the emergence of cooperation. Specifically, we show that a high degree of self-retention (D_{ii}) in all patches – that is a situation with low migration rates – is sufficient to ensure cooperation.

Proposition 4. *Let patch i be the patch with smallest self-retention parameter. For sufficiently large D_{ii}, complete cooperation over all N concessions can be sustained as an equilibrium outcome.*

Intuitively, if all patches have sufficiently high self-retention, then the externality is relatively small, which (we show) implies that the *renewal* effect outweighs the *mining* effect in all patches. When spatial externalities are not too large, the concession instrument overcomes the externality caused by strategic interaction. If self-retention is very low, then a large externality exists, and it may be more difficult to sustain cooperation. The formal result is not quite as straightforward because D_{ii} also plays a role in e_j^* for *all* patches j, and thus affects defection incentives in all patches. Accounting for all of these dynamics, we obtain:

Proposition 5. *Let patch i be the patch with the largest self-retention parameter. For sufficiently small D_{ii}, cooperation will not emerge as an equilibrium outcome provided the following condition is satisfied:*

$$p_i \sum_{j \neq i} D_{ji} g(e_j^*) < \sum_{j \neq i} D_{ij} p_j g'(e_i^*) e_i^*. \tag{13}$$

Proposition 5 establishes that if the resource is highly mobile (sufficiently low self-retention rates), then cooperation might be destroyed. This result relies on the fact that economic benefits mainly depend on resource immigration. Condition (13) compares concessionaire i's cooperation benefits due to incoming resources and the sum of benefits other concessionaires may get from the resource migrating from patch i. This condition contrasts the benefits and losses of concessionaire i due to species movement.

3.3 Effect of tenure duration

Thus far we have focused on inherent features of patches and the system as a whole that affect a concessionaire's incentives to cooperate or defect. But Condition (12) also depends explicitly on the tenure length T. Indeed, the length of the concession might play a role in how concessionaires make their private decisions, and thus this is a policy issue for a concession regime to be successful. This subsection focuses on the optimal determination of T.

A basic tenet of property rights and resource exploitation is that more secure property rights lead to more efficient resource use. Apropos of this observation, Costello and Kaffine (2008) found that longer tenure duration indeed increased the likelihood of cooperation in limited-tenure (though aspatial) fishery concessions. So at first glance, we might expect a similar finding here. In fact, we find the opposite, summarized as follows:

Proposition 6. *For sufficiently long tenure duration, T, cooperation cannot be sustained as an equilibrium outcome.*

Proposition 6 seems to contradict basic economic intuition; it states that if tenure duration is long, it is impossible for the regulator to induce socially-optimal extraction of a spatially-connected resource by using the instrument analyzed here. But upon deeper inspection this result accords with economic principles, due to defection incentives driven by spatial externalities in this setting. Consider the case of very long tenure duration - in the extreme, when tenure is infinite, gains from defection always outweigh gains from cooperation. The promise of renewal has no effect on incentives, so each concessionaire acts in his own best interest, which involves the defection path identified in Proposition 1.[21] Proposition 6 also holds in an extended version of the instrument, where the regulator can (with some probability $f < 1$) terminate tenure immediately upon defection (rather than waiting until the end of the tenure block in which defection occurs).[22] Indeed, the optimal defection will retain the qualitative features of Proposition 1: $\bar{e}_{it} = \bar{e}_i(f) > 0$ at every period but the last one, and $\bar{e}_{ikT-1} = 0$ (as long as $1 - f$ is large enough so that $\bar{e}_i(f) > 0$ holds). Since cooperation payoffs remain unchanged, results in Proposition 3 and thus Proposition 6 remain valid qualitatively under this extension. Other interpretations of this extension are interesting. On one hand, f could reflect stock assessment uncertainty (so f is the probability of correct assessment). Then the instrument exhibits some robustness to imperfect stock assessment (when f is large enough). On the other hand, if it denotes the probability that stock assessment is actually implemented, then the expected cost of monitoring would decrease as the tenure length increases.

Short tenure duration harbors two incentives for cooperation: First, when tenure is short, the payoff from defection is relatively small because the concessionaire has few periods in which to defect. Second, the renewal promise is significant because it involves a much longer future horizon that does the current tenure block. This result obtains because the spatial externality of resource dispersal drives a wedge between the privately optimal decision and the socially optimal one.

In fact, we can characterize a threshold tenure length for which concessionaire i will defect if $T_i > \bar{T}_i$, and owner i will cooperate otherwise. The time-threshold

[21]Following our approach above, we focus on the incentives of any given concessionaire when all other concessionaires follow the equilibrium strategies defined in Proposition 2. A more complex set of strategies (trigger or other punishment strategies) might weaken Proposition 6; we briefly return to this issue by providing one result (Proposition 9) in the Appendix.

[22]In this extended version we maintain the assumption that, at the last period of the tenure block, the regulator can terminate tenure immediately upon defection with probability one.

for concessionaire i can be written as follows:

$$\bar{T}_i = 1 + \frac{\ln\left(\frac{\delta(\bar{x}_i - x_i^*) + e_i^* - \bar{e}_i}{\delta \bar{x}_i - \bar{e}_i}\right)}{\ln(\delta)} \tag{14}$$

Consequently, it can be shown that cooperation is sustained by assigning to all N concessionaires a threshold value, which we summarize as follows:

Proposition 7. *Assume the following holds for concessionaire i:*

$$\delta x_i^* - e_i^* > (1-\delta)\left(\delta \bar{x}_i - \bar{e}_i\right); \tag{15}$$

Then there exists a threshold value $\bar{T} = \min_i\{\bar{T}_i\} > 1$ *such that cooperation is sustained as an equilibrium outcome if and only if* $T \leq \bar{T}$.

The condition in Proposition 7 is a restatement of the result of Proposition 3 for a tenure period of $T = 2$. Thus, by Proposition 3 we know that a tenure period of 1 will guarantee cooperation. It turns out that the threshold tenure length, $\bar{T} = \min_i\{\bar{T}_i\}$, depends on patch level characteristics. Here, we briefly examine the dependence of $\bar{T}_i$ on patch, and system-level characteristics.

Because the variables $\bar{e}_i$, $\bar{x}_i$, e_i^*, and x_i^* all depend on model parameters, deriving comparative statics is non-trivial. Recalling the comparative statics which addresses how concessionaire i's willingness to cooperate depends on parameters of the problem, intuitively similar results will be obtained here. Indeed, we obtain qualitatively similar results; because of this similarity, we relegate them to the Appendix (in Section B).

4 Robustness of the instrument

To maintain analytical tractability, and to sharpen the analysis, we have made a number of simplifying assumptions. Here we examine the consequences of two noteworthy assumptions. First, we examine whether a finite horizon (rather than infinite, as is assumed above) can still induce cooperation. Finally, we briefly explain why the emergence of cooperation is robust to the case of stock-dependent costs.

4.1 The case of a finite horizon

In this analysis, concessionaires must trade off a finite single tenure block against an infinite number of renewed tenure blocks. Even though this is not an unreasonable assumption per se, it raises the question of whether the instrument is still effective at inducing cooperation when the horizon is finite. Suppose time ends after K

tenure blocks where $1 < K < \infty$ after which all concessionaires' payoffs are zero. We prove here that provided cooperation was subgame perfect under an infinite horizon, it remains subgame perfect under the finite horizon problem described here.

Proposition 8. *Suppose time ends after the K^{th} tenure block. Provided that the following condition holds for any i:*

$$\left(1-\delta^T\right)(\delta x_i^* - e_i^*) - \delta^T\left(1-\delta^{T-1}\right)\left(\delta\bar{\bar{x}}_i - \bar{e}_i\right) > \left(1-\delta^{T-1}\right)(\delta\bar{x}_i - \bar{e}_i)\,, \qquad (16)$$

then the instrument induces cooperation for the first $K-1$ tenure blocks of the finite horizon problem. This condition is more stringent than the one ensuring cooperation over an infinite time horizon.

The key insight from Proposition 8 is that the planner's time horizon need not be infinitely long for the limited-tenure concession instrument to be effective. Indeed, the proposition provides a sufficient condition for complete cooperation, and thus socially-optimal extraction rates, to occur across the entire spatial domain, despite the limited time horizon. Condition (16) is a new statement of the condition provided in Proposition 3. The right-hand side term (the gains from defection) is still the same, while the left-hand side term is more complex. Concessionaires anticipate that they will not be renewed at the end of the final tenure block. As such, they follow the cooperative strategy during the first tenure blocks, then they *all* deviate and choose residual stock $\bar{e}_i$ before mining the resource in their respective areas in the final period. The (discounted) payoffs when concessionaires cooperate during the entire process, $\left(1-\delta^T\right)(\delta x_i^* - e_i^*)$, are now lower due to the increase in the defection payoffs in the final period $\delta^T\left(1-\delta^{T-1}\right)\left(\delta\bar{\bar{x}}_i - \bar{e}_i\right)$. By comparison with the case of an infinite time horizon, shorter time horizons require more stringent conditions for cooperation to be effective. Thus, longer time horizons are most effective. The best choice of tenure duration, however, is less clear-cut. Long tenure duration might result in the failure of the instrument, while short duration might entail higher transaction costs. This suggests a trade-off between shorter and longer tenure durations.

4.2 The case of stock-dependent costs

So far, we have assumed that extraction costs are linear in the amount extracted. We wonder whether the instrument is robust when marginal costs are stock-dependent. For example, the expression of concessionaire i's payoffs during period t could be as follows:

$$\Pi_{it} = p_i\left(x_{it} - e_{it}\right) - \int_{e_{it}}^{x_{it}} c_i(s)ds$$

where $c_i'(s) < 0$ is continuously differentiable. Our aim is to explain briefly why the logic of Proposition 3 (the main result analyzing the performance of the instrument) remains valid here. The proof relies mainly on two arguments.[23] First, the optimal defection strategy does not depend on the tenure block considered. Second, for the tenure block during which defection occurs, patch owner i's optimal defection strategy in period t remains time and state independent. These two features remain valid, even though the characterization of the optimal defection strategy differs. The conditions ensuring the emergence of complete cooperation differ from Conditions (12) also, but the qualitative conclusion of Proposition 3 remains valid. We conclude that while using stock-dependent marginal cost complicates the proofs and exposition of the results, there are still conditions under which the instrument incentivizes the agents to manage the resource in a socially optimal way. Overall, since the same logic applies, this suggests it is unlikely to overturn the other main findings (for instance, the failure of the instrument for sufficiently long tenure lengths).

5 Discussions and extensions

5.1 Stock assessment and monitoring

We now discuss the issue of stock assessment and monitoring. Indeed, stock assessment may be difficult to implement, and the cost of monitoring may thus prove to be important. There are different points that need to be highlighted. First, the alternative form of the instrument discussed in Section 3.3 exhibits some robustness to imperfect stock assessment; moreover, it would actually decrease the expected cost of monitoring. Specifically, this alternative form accounts for the fact that the probability that stock assessment is actually implemented may be less than one, and the expected cost of monitoring would thus drastically decrease as the tenure length increases.

Secondly, several contributions suggest that regular and proper stock assessment is a mandatory part of a well-designed concession system, even if the system is based on harvest. As mentioned in the Introduction, Jarvis and Wilen (2016) explain that, in the case of Chile, in order for the government to determine a well-designed total allowable catch (TAC) for each TURF, a mandatory annual stock assessment has to be carried out by technical consultants approved by the government and paid by TURF members. This requirement of proper assessment is further supported by Hilborn et al. (2005), who explain that successful concession systems

[23]We provide the key arguments of the proof. The full details are available as supplementary material at the end of the appendix in Propositions 10 and 11.

based on harvest levels tend to engage in active research programs funding stock assessments directly, and by Wilen et al. (2012), who provide another example of successful TURF initiatives in Japan, where scientific advice regarding stock assessment is provided to define sustainable TACs. Following this line of reasoning, a logical implication is that, for a system to be effective, proper stock assessment is mandatory, whether the system is based on harvest or on (residual) stock requirements. As such, it is difficult to sustain that our system will be more demanding in terms of monitoring: both types of system will be demanding with respect to this dimension.

Moreover, it seems plausible that endogenous enforcement would be strengthened by parameters that induce persistent cooperation over time, particularly when monitoring involves capital expenditures.[24] Enforcement issues may be driven (among other factors) by lack of legitimacy or the "need" for profit versus risk of deterrence (Hatcher et al. (2000)). In developing countries this motivation might be greater than in developed ones; this might underscore enforcement issues. Yet, initiatives like community-based fisheries might improve the legitimacy of the proposed instrument while reducing monitoring costs.[25] These institutional arrangements are receiving increasing attention in developing countries. Since participation in the organization of the concession instrument can contribute to building its legitimacy, community-based fisheries might constitute an interesting option to increase enforcement in such areas. Finally, real-world cases of concessions (such as Territorial Use Rights Fisheries) suggest that science-based stock assessment is an integral part of the property rights system, which makes it less onerous for managers to monitor stocks and assess patch-specific characteristics. Cooperation between communities and government might help to decrease the cost of stock assessment, which may provide incentives for active engagement in assessment practices, consistent with Hilborn et al. (2005). Indeed, it allows increasing interactions between concession owners and public-sector scientists, who might contribute to stock assessment, thus decreasing the assessment cost in return for access to the data collected.

Finally, we can also note an important feature of our analysis. If stock assess-

[24]Concession rights might strengthen endogenous enforcement, and this could be rewarded via management certification, as occurs in many fisheries. Moreover, certification may provide improvements in market access (Auld et al. (2008)). Thus, as suggested by Rico et al. (2017), certifications might decrease transaction costs and strengthen agents' monitoring activities; both mechanisms would plausibly ease the conditions under which our instrument induces the cooperative outcome.

[25]Monitoring costs are very likely to be lower compared to the case of state monitoring. Legitimacy may increase because of active and engaged leadership (Crona et al. 2017).

ments require a fixed cost each year, then they also influence the social planner's optimized payoff, but will not affect her optimal choice of escapement. This follows from Section 2.1.1. This will also be the case for concessionaires under the concession instrument proposed here: their optimized payoffs will be affected, but their optimal choice to cooperate/defect will not. In other words, the existence of monitoring costs will affect the agents' optimized payoff, but it will not affect the ability of the instrument to act as an effective cooperation device.

5.2 Comparison with other potential policies

Our paper explicitly compares three alternative policies. First, we examine the social planner's problem. In that case, all spatial movement is internalized, and the result is Equation 4 in each and every patch, which yields the highest possible present value of the spatially-connected resource. Second, we examine the completely decentralized policy where spatial property rights are allocated, but without coordination across properties. This leads to over-extraction in all patches, and is shown in Equation 7. Finally, we examine a wide range of possible concession instruments (longer and shorter tenure duration, higher and lower target stocks). We derive the parameters of the concession contract that guarantee that the socially optimal level of extraction will take place every period.

Beyond these policies, it might be useful to discuss other concession approaches, even though a full comparison is beyond the scope of the present paper, and more so as these other instruments potentially may not achieve the socially optimal outcome. First, one could consider concessions with conditionality based on a maximum total harvest. In this case, the characterization of the socially optimal paths obtained in Section 2.1.1 together with the reasoning used to characterize the optimal defection path in Proposition 1 allow to conclude that such an instrument would not achieve the socially optimal outcome. Even if total harvest requirements are satisfied by the end of the tenure, it will induce over-harvest in certain time periods. In other words, it cannot ensure that the socially optimal outcome is implemented at any given time period.

Second, one could consider concessions with conditionality based on a maximum total annual harvest, the maximum total harvest for a any time period. In other words, this instrument would be entirely similar to our proposed system, except that the requirements for tenure renewal would be based on harvest target levels at every time period. Again, if one focuses on the capacity of this instrument to induce the socially optimal outcome, then the conditions under which this instrument induces does so are likely to be equivalent to those related to our proposed instrument. Indeed, by the identity $h_{it} = x_{it} - e_{it}$, one could choose either harvest or residual stock as the main variable defining the instrument (because given the state of the system ($\mathbf{x}_t$) one derives directly from the other). Moreover, as we discuss it in Section 5.1, both types of instrument require proper and regular stock assessment.

Third, one could consider policies that do not use TURFs but instead use property rights over the resource, as it is quite common across the world in managing mobile resources. The main problem here can be highlighted by coming back to the characterization of the socially optimal escapement levels, which is given by expression (4). Since biological growth, dispersal, and economic returns are patch-specific, the optimal policy will vary across patches. Specifically, equation 4 highlights immediately that the optimal policy depends on patch-specific net prices, growth, and dispersal and self-retention parameters. So the socially optimal outcome is spatially explicit, while using property rights over the resource implies that one would abstract from spatial features and propose a non-spatially explicit instrument. As a consequence, such an instrument can not achieve the socially optimal outcome, unlike our proposed instrument. On the other side, as explained in Section 5.1 it is not clear that property rights over the resource would be less demanding in terms of the related costs of monitoring if the regulator/manager is willing to ensure that this policy be as effective as possible.[26]

Finally, we conclude this section by discussing an extension of the present instrument. While we consider an instrument where the size of concessions is not endogenously chosen by the manager, the size of TURFS may be part of the manager's decision and thus be used to define another type of instrument. It is still possible here to derive some insights about changes in the size of patches on the agents' willingness to cooperate. Indeed, if size is somehow related to biological productivity, then one can rely on the findings obtained in Section 3.2 to derive some insights about the effects of variations in the size of connected patches on the agents' incentives to cooperate. These results suggest that such variations may have a nuanced effect. Indeed, based on Section 3.2 agent i will be more likely to cooperate as the size of an adjacent property increases, but the effect of an increase in the size of agent i's own property on his incentives to do so is ambiguous. As such, the design of a policy that would be specifically based on the size of the patches would have to account for a variety of direct and indirect effects. This will raise a sufficiently large number of questions to deserve a separate contribution.

[26] We refer to Wilen et al. (2012) for a discussion of other advantages of spatially explicit instruments compared to species-based systems.

6 Conclusion

This paper has spawned from two basic observations: First, that limited-duration concessions are a prominent version of property rights used to manage diverse natural resources in many countries, and second, that some of the natural resources managed with such instruments are mobile. Despite their widespread use, spatial concessions have received almost no attention from economists. We have studied the efficiency of a decentralized property rights system over a spatially-connected renewable natural resource, such as a fishery. To overcome the excessive harvest that is incentivized by decentralization, we propose a new instrument based on limited-tenure concessions with the possibility of renewal. Somewhat surprisingly, we find that this instrument can be designed to be extremely effective in overcoming the tragedy of the commons: this instrument can often induce the concessionaires to implement the socially optimal outcome, completely neutralizing the externality. This is remarkable as it does not rely on any transfers or side-payments, and seems to accord with certain real-world institutions that use limited-term concessions to manage natural resources. This suggests a strong rationale for TURF-like initiatives (over, say, single-species or harvest-based management), and adds further to the benefits already outlined by Wilen et al. (2012). While some critics maintain that TURF systems are appropriate only for sedentary species (that do not move), this study provides a mechanism by which even mobile species can be efficiently managed using TURFs. This is consistent with several cases of TURFs managing medium or high mobility species (Auriemma et al. 2014). Second, unlike an initial intuition, the effect of a longer time horizon is usually negative. This is in contrast with the case without strategic spatial interactions as depicted in Costello and Kaffine (2008).

Several observations bear further discussion. First, we have considered a quite secure tenure system: renewal is ensured as long as the target is attained. This allows us to focus on the effects of the spatial characteristics of our problem. Introducing a probability of renewal (as in Costello and Kaffine (2008)) would require characterizing the threshold value over which cooperation could be induced; a version of this approach was discussed in Section 3.3.

Second, several additional extensions remain. We could analyze situations where there is imperfect (incomplete) information, or where the growth of the resource is stochastic. As long as patches are symmetric regarding the anticipated effects, we expect no drastic change in the qualitative results. The incentives of regulators in offering concessions may also be an interesting issue to explore. In this setting, the regulator could be viewed as a Stackelberg leader. The focus here was on identifying design parameters that induce concessionaires to cooperate. A next step could involve introducing different regulators' objectives. Finally, depending on the situations there could be density-driven movement, or different timing of growth. Such features reduce model tractability and neither render our results moot nor obviously make the analysis more realistic.

Overall, our results suggest that if implemented with care, limited tenure spatial concessions can achieve socially-optimal outcomes and yet still allow concessionaires to make decentralized decisions all while the government retains regulatory authority to require adherence to certain restrictions. They also suggest that such instruments may not only have attractive intuitive appeal, but that if designed and implemented with care, they could be theoretically grounded in economic efficiency.

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Appendix

Proof of Proposition 1

We proceed by backward induction. We first consider the case where $g_i'(0) > \frac{1}{\delta D_{ii}}$. At final period $kT-1$, concessionaire i's problem is to maximize

$$\max_{e_{ikT-1}\geq 0} p_i \left(x_{ikT-1} - e_{ikT-1}\right)$$

Using the first order condition enables us to conclude immediately that $\bar{e}_{ikT-1} = 0$, that is, concessionaire i extracts the entire stock at the final period. Now, moving backward, at period $T-2$, this concessionaire's problem becomes:

$$\max_{e_{ikT-2}\geq 0} p_i \left[x_{ikT-2} - e_{ikT-2} + \delta\left(\sum_{j\neq i} D_{ji}g(\bar{e}_{jkT-2}) + D_{ii}g(e_{ikT-2}) - \bar{e}_{ikT-1}\right)\right].$$

Using the first order condition (with respect to $\bar{e}_{ikT-2}$) and $\bar{e}_{ikT-1} = 0$, we obtain that $\bar{e}_{ikT-2}$ is characterized by the following condition:

$$\delta D_{ii} g'(\bar{e}_{ikT-2}) = 1.$$

This is so since $\bar{e}_{ikT-2} = 0$ is ruled out by the lower bound on the value of $g'(0)$, and $\bar{e}_{ikT-2} = x_{ikT-2}$ is ruled out if $x_{ikT-2} > (g')^{-1}\left(\frac{1}{\delta D_{ii}}\right)$ holds, which is satisfied as we will later show. Repeating the same argument of backward induction it is easily checked that any equilibrium residual stock level $\bar{e}_{it}$ (where $(k-1)T \leq t \leq kT-3$) is characterized by the same condition provided that $x_{it} > (g')^{-1}\left(\frac{1}{\delta D_{ii}}\right) = \bar{e}_i$ for any period t. In the present case, we have, by definition of $\bar{e}_i$ and concavity of $g(.)$:

$$g(\bar{e}_i) > \bar{e}_i g'(\bar{e}_i) = \frac{\bar{e}_i}{\delta D_{ii}}$$

which implies that $D_{ii}g(\bar{e}_i) > \frac{\bar{e}_i}{\delta} \geq \bar{e}_i$ for $\delta \in]0,1]$ and thus, by the definition of x_{it} for any period $(k-1)T \leq t \leq kT-1$ we deduce that $x_{it} > \bar{e}_i$ for any tenure block but the first one. Even if concessionaire i chooses to defect at the very beginning, since $x_{i0} > (g')^{-1}\left(\frac{p_i}{\delta\sum_j D_{ij}p_j}\right) > (g')^{-1}\left(\frac{1}{\delta D_{ii}}\right)$ by assumption, the same conclusion follows in this case. This concludes the proof of the first case. The proof of the second case follows quickly from backward induction arguments because of the upper bound on the value of $g'(0)$.

Proof of Proposition 2

Compliance by concessionaire i requires that $e_{it} \geq e_i^* \ \forall t$. Now assume that there is a time period t during which concessionaire i chooses $e_{it} > e_i^*$: this implies that, for e_{it} to be strictly profitable we must have:

$$p_i\left(1+\delta\right)\left(x_i^* - e_i^*\right) < p_i\left[\left(x_i^* - e_{it}\right) + \delta\left(\sum_{j\neq i} D_{ji}g\left(e_j^*\right) + D_{ii}g\left(e_{it}\right)\right)\right].$$

Simplifying this inequality, we obtain:

$$\delta D_{ii}\left(g\left(e_{it}\right)-g\left(e_i^*\right)\right)>e_{it}-e_i^*. \tag{17}$$

Since $g(.)$ is continuously differentiable and increasing, we know there exists $e_i \in]e_i^*, e_{it}[$ such that $g\left(e_{it}\right)-g\left(e_i^*\right)=\left(e_{it}-e_i^*\right)g'(e_i)$ and we can rewrite expression 17 as follows:

$$\delta D_{ii}\left(e_{it}-e_i^*\right)g'(e_i)>e_{it}-e_i^* \Leftrightarrow g'(e_i)>\frac{1}{\delta D_{ii}}=g'(\bar{e}_i).$$

We thus deduce that (since $g(.)$ is strictly concave) $e_i^*<e_i<\bar{e}_i$, which is a contradiction (since $e_i^* \geq \bar{e}_i$ as explained in subsection 2.1.2). This implies that $e_{it}=e_i^*$ for any time period t, which concludes the proof.

Proof of Proposition 3

If concessionaire i deviates during tenure $k+1$ (while other concessionaires follow their equilibrium strategies) then this concessionaire's payoff is $\Pi_i^d=p_iA$, where :

$$A=\left[x_{i0}-e_i^*+\frac{\delta(1-\delta^{kT})}{1-\delta}\left(x_i^*-e_i^*\right)+\delta^{kT}\left(e_i^*-\bar{e}_i\right)+\frac{\delta^{kT+1}(1-\delta^{T-1})}{1-\delta}\left(\bar{x}_i-\bar{e}_i\right)+\delta^{(k+1)T-1}\bar{e}_i\right].$$

Now, using Condition (9), we compute $\Pi_i^c-\Pi_i^d=p_iB$, with:

$$\begin{aligned} B &= \left[\frac{\delta^{kT+1}}{1-\delta}\left(x_i^*-e_i^*\right)-\delta^{kT}\left(e_i^*-\bar{e}_i\right)-\frac{\delta^{kT+1}(1-\delta^{T-1})}{1-\delta}\left(\bar{x}_i-\bar{e}_i\right)-\delta^{(k+1)T-1}\bar{e}_i\right] && (18)\\ &= \frac{\delta^{kT}p_i}{1-\delta}\left[\delta x_i^*-e_i^*-\left(1-\delta^{T-1}\right)\left(\delta\bar{x}_i-\bar{e}_i\right)\right]. && (19) \end{aligned}$$

The conclusion follows from Equality (19).

Proof of Proposition 4

We will show that concessionaire i does not have incentives to deviate, which will be sufficient to prove the result. First, we prove that the concessionaire does not have incentive to deviate from the initial period until the end of the first tenure. From the proof of Proposition 3 (using the expression of the difference in payoffs (41) when $k=0$) we know that:

$$\begin{aligned} \Pi_i^c-\Pi_i^d &= p_i\left[\bar{e}_i-e_i^*+\frac{\delta}{1-\delta}(x_i^*-e_i^*)-\frac{\delta(1-\delta^{T-1})}{1-\delta}(\bar{x}_i-\bar{e}_i)-\delta^{T-1}\bar{e}_i\right]\\ &= \frac{p_i}{1-\delta}\left[(1-\delta)(\bar{e}_i-e_i^*)+\delta(x_i^*-e_i^*)-\delta(1-\delta^{T-1})(\bar{x}_i-\bar{e}_i)-\delta^{T-1}(1-\delta)\bar{e}_i\right]. \end{aligned}$$

When D_{ii} gets arbitrarily close to one, the characterizations of $\bar{e}_i$ and e_i^* enable to conclude that $\bar{e}_i$ gets arbitrarily close to e_i^*. We can deduce that $\Pi_i^c-\Pi_i^d$ gets arbitrarily close to the following expression:

$$p_i\left[\frac{\delta^T}{1-\delta}(x_i^*-e_i^*)-\delta^{T-1}e_i^*\right]=\frac{\delta^{T-1}p_i}{1-\delta}(\delta x_i^*-e_i^*). \tag{20}$$

Again, when D_{ii} converges to one, x_i^* gets arbitrarily close to $g(e_i^*)$. Then, for $D_{ii}=1$ we know that $1=\delta g'(e_i^*)$ and we can rewrite Equation (20) as follows:

$$\frac{\delta^T}{1-\delta}(\delta x_i^*-e_i^*)=\frac{\delta^T}{1-\delta}[\delta g(e_i^*)-\delta g'(e_i^*)e_i^*]=\frac{\delta^{T+1}}{1-\delta}[g(e_i^*)-g'(e_i^*)e_i^*]. \tag{21}$$

The concavity of g (together with the fact that $g(0) = 0$) enables to quickly deduce that $g(e_i^*) - g'(e_i^*)e_i^*$ is positive. Thus, for $D_{ii} = 1$ we know that $\Pi_i^c - \Pi_i^d > 0$ which, by a continuity argument, enables to conclude that the above deviation is not profitable (for concessionaire i) for sufficiently large (but less than one) values of self retention of this concessionaire's patch.

Second, we conclude the proof by showing that concessionaire i does not have incentives to deviate during any other tenure block. Consider that defection might occur during tenure block $k+1$. We can rewrite the difference in payoffs as follows:

$$\Pi_i^c - \Pi_i^d = p_i \left[\delta^{kT} (\bar{e}_i - e_i^*) + \sum_{t=kT+1}^{(k+1)T-1} \delta^t \left(x_i^* - e_i^* - \bar{x}_i + \bar{e}_i \right) + \frac{\delta^{(k+1)T}}{1-\delta} (x_i^* - e_i^*) - \delta^{(k+1)T-1} \bar{e}_i \right].$$

When D_{ii} gets arbitrarily close to one, the characterizations of $\bar{e}_i$ and e_i^* enable to conclude that $\bar{e}_i$ gets arbitrarily close to e_i^*, and $\bar{x}_i$ gets arbitrarily close to x_i^* (since g is continuous). We can deduce that $\Pi_i^c - \Pi_i^d$ gets arbitrarily close to $p_i \frac{\delta^{(k+1)T-1}}{1-\delta} (\delta x_i^* - e_i^*)$. We can then deduce that the deviation is not profitable for concessionaire i (for sufficiently large values of D_{ii}). This proves that concessionaire i does not have the incentive to defect. The same reasoning holds for any other concessionaire, which concludes the proof.

Proof of Proposition 5

Using Proposition 3, we know that concessionaire i would defect if the following condition is satisfied:

$$\delta x_i^* - e_i^* < \left(1 - \delta^{T-1}\right) (\delta \bar{x}_i - \bar{e}_i).$$

The right hand side of this inequality increases as T increases. Indeed, the derivative of this term as a function of T is $-\delta^{T-1} ln(\delta) (\delta \bar{x}_i - \bar{e}_i)$, which is positive, since $ln(\delta) < 0$ and $\delta \bar{x}_i - \bar{e}_i$ is positive.[27] As such, for any tenure length T there will be defection if $\delta x_i^* - e_i^*$ is negative. Now, if D_{ii} is sufficiently small, then $\bar{e}_i = 0$ and we focus on cases where e_i^* is still positive. We examine the extreme case where $e_i^* > 0$ even when D_{ii} is equal to zero. Using the characterization of e_i^*, we can rewrite $\delta x_i^* - e_i^*$ as follows:

$$\delta x_i^* - e_i^* = \delta \left[\sum_{j \neq i} D_{ji} g(e_j^*) - \sum_{j \neq i} D_{ij} \frac{p_j}{p_i} g'(e_i^*) e_i^* \right].$$

If the left hand side of this equality is negative (which is the case provided that Condition 13 holds), then $\delta x_i^* - e_i^*$ is negative, which concludes the proof.

Proof of Proposition 6

We claim that, as T gets arbitrarily large, any concessionaire i will defect from full cooperation. Let us assume that any concessionaire $j \neq i$ follows a full cooperation path; we now analyze concessionaire i's incentives to defect. One possible deviation is described in Proposition 1. Specifically, concessionaire i might deviate from the initial period until period T. Then this

[27] Indeed, $\delta \bar{x}_i - \bar{e}_i = \delta \sum_{j \neq i} D_{ji} g(e_j^*) + \delta D_{ii} g(\bar{e}_i) - \delta D_{ii} g'(\bar{e}_i) \bar{e}_i = \delta \sum_{j \neq i} D_{ji} g(e_j^*) + \delta D_{ii} \left(g(\bar{e}_i) - g'(\bar{e}_i) \bar{e}_i \right) > 0$ since the second term is positive by concavity of the growth function g. If $D_{ii} = 0$ then $\delta \bar{x}_i - \bar{e}_i = \delta \bar{x}_i$ is positive too.

concessionaire will not be renewed. According to Proposition 1, this concessionaire's payoff from defecting will then be equal to Π_i^d.

We now prove that $\Pi_i^c - \Pi_i^d \leq 0$ for sufficiently large values of T. Using the proof of proposition 3 (specifically, the difference in payoffs (41) when $k = 0$) we have:

$$\Pi_i^c - \Pi_i^d = p_i \left[\bar{e}_i - e_i^* + \frac{\delta}{1-\delta}(x_i^* - e_i^*) - \frac{\delta(1-\delta^{T-1})}{1-\delta}(\bar{x}_i - \bar{e}_i) - \delta^{T-1}\bar{e}_i \right].$$

When T gets arbitrarily large, $\Pi_i^c - \Pi_i^d$ gets close to

$$p_i \left[\bar{e}_i - e_i^* + \frac{\delta}{1-\delta}(x_i^* - e_i^* - \bar{x}_i + \bar{e}_i) \right]. \tag{22}$$

Now, we know that $x_i^* - \bar{x}_i = D_{ii}(g(e_i^*) - g(\bar{e}_i))$ and we obtain the following inequality (by concavity of function g):

$$x_i^* - \bar{x}_i = D_{ii}(g(e_i^*) - g(\bar{e}_i)) < D_{ii}g'(\bar{e}_i)(e_i^* - \bar{e}_i).$$

This enables us to deduce the following inequality regarding Equation (22):

$$\frac{p_i}{1-\delta}[\delta D_{ii}(g(e_i^*) - g(\bar{e}_i)) - (e_i^* - \bar{e}_i)] < \frac{p_i}{1-\delta}[\delta D_{ii}g'(\bar{e}_i) - 1](e_i^* - \bar{e}_i). \tag{23}$$

But we know (from the characterization of $\bar{e}_i$) that $\bar{e}_i$ satisfies $\delta D_{ii}g'(\bar{e}_i) = 1$, which implies that the right hand side of the above inequality is equal to zero. We conclude that the Expression (22) is negative which, by a continuity argument, implies that $\Pi_i^c - \Pi_i^d \leq 0$ for sufficiently large values of T. This concludes the proof.

Proof of Proposition 7

For a given concessionaire i, consider $\bar{T}_i$ defined implicitly by:

$$\bar{e}_i - e_i^* + \frac{\delta}{1-\delta}(x_i^* - e_i^*) - \frac{\delta(1-\delta^{\bar{T}_i-1})}{1-\delta}(\bar{x}_i - \bar{e}_i) - \delta^{\bar{T}_i-1}\bar{e}_i = 0.$$

Since the characterization of $\bar{e}_i$ and e_i^* ensure that residual stock levels (and thus stock levels) do not depend on the value of the time horizon, we can differentiate the left hand side of the equality as a function of T, and we obtain the following expression:

$$\delta^{T-1}\frac{ln(\delta)}{1-\delta}(\delta\bar{x}_i - \bar{e}_i)$$

which is negative since $ln(\delta) < 0$ as $0 < \delta \leq 1$ and $\delta\bar{x}_i - \bar{e}_i$ is positive (as shown in the proof of Proposition 5). This implies that the left hand side of the equality is a decreasing and continuous function of T (where T is assumed to take continuous values). Since the proof of Proposition 2 implies that this function takes on negative values as T becomes large, if we can prove that it has a positive value when $T = 2$ this would imply that $\bar{T}_i$ is uniquely defined and that $\bar{T}_i > 1$.[28] Then, again using the proof of Proposition 4 enables us to conclude that concessionaire i will

[28] Keep in mind that $\bar{T}_i$ is assumed to take continuous values in the proof. Now coming back to the fact that it is actually discrete, the argument of the proof implies that $\bar{T}_i$ is at least equal to 2.

have incentives to defect as soon as the renewal time horizon is larger than $\bar{T}_i$.

For $T = \mathbf{2}$ the value of the function is given by the following expression:

$$\bar{e}_i - e_i^* + \frac{\delta}{1-\delta}\left(x_i^* - e_i^*\right) - \delta\bar{x}_i = \frac{1}{1-\delta}\left[\delta x_i^* - e_i^* - (1-\delta)\left(\delta\bar{x}_i - \bar{e}_i\right)\right].$$

Assumption (15) implies that the right hand side of this equality is positive, which enables us to conclude about the existence and uniqueness of

$$\bar{T}_i = \mathbf{1} + \frac{ln\left[\frac{\delta\bar{x}_i - \bar{e}_i - (\delta x_i^* - e_i^*)}{\delta\bar{x}_i - \bar{e}_i}\right]}{ln(\delta)}.$$

This concludes the proof of the result since $\bar{T} = \min_i \bar{T}_i$ qualifies as the appropriate threshold value.

Proof of Proposition 8

First, consider what happens during the final tenure block K. Using backward induction reveals that any concessionaire i's strategy during that block is characterized by $e_{i,KT-1} = 0$, and for any other period $(K-1)T \le t \le KT-2$ we have $e_{i,t} = \bar{e}_i$ where $1 = \delta D_{ii} g'(\bar{e}_i)$.

In other words, anticipating that he will not get renewed for sure at the end of the final tenure block, any concessionaire i will defect. But in order to reach the final tenure block all concessionaires will have managed the resource cooperatively (for the first $K-1$ tenure blocks). Thus, cooperative concessionaires will play as follows (the first period of the first tenure block being $t = 0$):

- during the first $K-1$ tenure blocks (thus from $t = 0$ to $t = (K-1)T-1$) concessionaire i chooses $e_i = e_i^*$: from $t = 1$ to $t = (K-1)T-1$ the stock level is $x_i = x_i^*$, at period $t = 0$ we has $x_i = x_{i,0}$;
- then, at period $t = (K-1)T$, concessionaire i chooses $e_i = \bar{e}_i$, and stock level at this same period $(K-1)T$ is still $x_i = x_i^*$;
- In all other periods of the final tenure block but the last one, concessionaire i chooses $e_i = \bar{e}_i$ and the stock level is $\bar{\bar{x}}_i = \sum_j D_{ji} g(\bar{e}_j)$;
- Finally, at $t = KT-1$ we have $e_i = 0$ and $x_i = \bar{\bar{x}}_i$.

This implies that the payoffs from cooperation are this time given by:

$$\Pi_i^c = p_i\left[x_{i,0} - e_i^* + \sum_{t=1}^{(K-1)T-1} \delta^t (x_i^* - e_i^*) + \delta^{(K-1)T}(x_i^* - \bar{e}_i) + \sum_{t=(K-1)T+1}^{KT-2} \delta^t (\bar{\bar{x}}_i - \bar{e}_i) + \delta^{KT-1}\bar{\bar{x}}_i\right].$$

Now, we have to consider concessionaire i's potential unilateral deviation strategy. Assuming that this concessionaire defects during tenure block $1 \le k < K$ (thus knowing that he will not be renewed following tenure block k) the timing of his strategy then becomes:

- From $t = 0$ to $t = (k-1)T-1$ concessionaire i chooses $e_i = e_i^*$: from $t = 1$ to $t = (k-1)T-1$ the stock level is $x_i = x_i^*$, at period $t = 0$ we have $x_i = x_{i,0}$;
- Then, at period $t = (k-1)T$, concessionaire defects by choosing $e_i = \bar{e}_i$, and the stock level at this same period $(k-1)T$ is still $x_i = x_i^*$;

- In all other periods of tenure block k but the last one, concessionaire i chooses $e_i = \bar{e}_i$ and the stock level is $x_i = \bar{x}_i$;
- Finally, at $t = kT - 1$ we have $e_i = 0$ and $x_i = \bar{x}_i$.

This implies that the payoffs from unilaterally deviating during tenure block $k < K$ are this time given by:

$$\Pi_i^d = p_i \left[x_{i,0} - e_i^* + \sum_{t=1}^{(k-1)T-1} \delta^t (x_i^* - e_i^*) + \delta^{(k-1)T} (x_i^* - \bar{e}_i) + \sum_{t=(k-1)T+1}^{kT-2} \delta^t (\bar{x}_i - \bar{e}_i) + \delta^{kT-1} \bar{x}_i \right].$$

Using the expressions of Π_i^c and Π_i^d, we obtain:

$$\Pi_i^c - \Pi_i^d = \frac{p_i \delta^{(k-1)T}}{1-\delta} \left\{ \left(1 - \delta^{(K-k)T}\right) [\delta x_i^* - e_i^* + (1-\delta)\bar{e}_i] + \delta(1 - \delta^{T-2}) \left[\delta^{(K-k)T}(\bar{\bar{x}}_i - \bar{e}_i) - (\bar{x}_i - \bar{e}_i)\right] \right.$$
$$\left. + \delta^{T-1}(1-\delta) \left[\delta^{(K-k)T} \bar{\bar{x}}_i - \bar{x}_i\right] \right\}$$
$$= \frac{p_i \delta^{(k-1)T}}{1-\delta} \left\{ \left(1 - \delta^{(K-k)T}\right) (\delta x_i^* - e_i^*) + \delta^{(K-k)T} \left(1 - \delta^{T-1}\right) \delta \bar{\bar{x}}_i - \left(1 - \delta^{T-1}\right) \left[\delta \bar{x}_i - \left(1 - \delta^{(K-k)T}\right) \bar{e}_i\right] \right\}.$$

This implies that the sign of $\Pi_i^c - \Pi_i^d$ is given by that of:

$$\Phi(k) := \left(1 - \delta^{(K-k)T}\right) (\delta x_i^* - e_i^*) + \delta^{(K-k)T} \left(1 - \delta^{T-1}\right) \delta \bar{\bar{x}}_i - \left(1 - \delta^{T-1}\right) \left[\delta \bar{x}_i - \left(1 - \delta^{(K-k)T}\right) \bar{e}_i\right]$$

Differentiating $\Phi(\cdot)$ with respect to k, we obtain:

$$\Phi'(k) = \delta^{(K-k)T} T ln(\delta) \left\{ \delta x_i^* - e_i^* - \left(1 - \delta^{T-1}\right) \left[\delta \bar{\bar{x}}_i - \bar{e}_i\right] \right\}. \tag{24}$$

By definition of $\bar{\bar{x}}_i$ we have $\bar{\bar{x}}_i \leq \bar{x}_i$. Suppose concessionaires cooperate in the infinite horizon problem, i.e. that:

$$\delta x_i^* - e_i^* > \left(1 - \delta^{T-1}\right) (\delta \bar{x}_i - \bar{e}_i), \tag{25}$$

Then we have:

$$\delta x_i^* - e_i^* - \left(1 - \delta^{T-1}\right) \left[\delta \bar{\bar{x}}_i - \bar{e}_i\right] > \delta x_i^* - e_i^* - \left(1 - \delta^{T-1}\right) (\delta \bar{x}_i - \bar{e}_i) > 0.$$

This implies that the term between brackets on the right hand side of Equality (24) is positive. Since $ln(\delta) < 0$ as $\delta \in (0, 1]$ we conclude that $\Phi'(k) < 0$ for any k. This means that willingness to cooperate is decreasing in k - the longer we wait to defect, the lower is their incentive to cooperate. This implies that $k = K - 1$ corresponds to the lowest possible value of $\Phi(k)$. In other words, if concessionaire i will defect, she will have the strongest incentive to do so late in the game. We then obtain:

$$\Phi(K-1) = \left(1 - \delta^T\right) (\delta x_i^* - e_i^*) + \delta^T \left(1 - \delta^{T-1}\right) \delta \bar{\bar{x}}_i - \left(1 - \delta^{T-1}\right) \left[\delta \bar{x}_i - \left(1 - \delta^T\right) \bar{e}_i\right].$$

The reasoning above implies that $\Phi(K-1) > 0$ is a necessary and sufficient condition to ensure that concessionaire i will not defect. This condition can be rewritten as follows:

$$\delta x_i^* - e_i^* > \frac{1 - \delta^{T-1}}{1 - \delta^T} \left\{ \delta \bar{x}_i - \left(1 - \delta^T\right) \bar{e}_i - \delta^{T+1} \bar{\bar{x}}_i \right\}.$$

This concludes the proof of the first part of the proposition.

Finally, we can show that Condition 16 is more stringent than the condition ensuring cooperation under the infinite horizon instrument (Condition 25). Indeed, we have:

$$\frac{1-\delta^{T-1}}{1-\delta^{T}}\left[\delta\bar{x}_i-\left(1-\delta^{T}\right)\bar{e}_i-\delta^{T+1}\bar{\bar{x}}_i\right]-\left(1-\delta^{T-1}\right)\left(\delta\bar{x}_i-\bar{e}_i\right)=\frac{1-\delta^{T-1}}{1-\delta^{T}}\delta^{T+1}\left(\bar{x}_i-\bar{\bar{x}}_i\right)>0.$$

This inequality implies that, as soon as Condition 16 is satisfied then Condition 25 is satisfied:

$$\delta x_i^*-e_i^*>\frac{1-\delta^{T-1}}{1-\delta^{T}}\left[\delta\bar{x}_i-\left(1-\delta^{T}\right)\bar{e}_i-\delta^{T+1}\bar{\bar{x}}_i\right]\Rightarrow\delta x_i^*-e_i^*>\left(1-\delta^{T-1}\right)\left(\delta\bar{x}_i-\bar{e}_i\right),$$

but the opposite does not always hold true. Full cooperation under the infinite horizon instrument is not sufficient to ensure the same result under the finite horizon version of the instrument. Still, there are conditions under which cooperation will persist under the finite horizon version.

Section 3.2 and comparative statics on the time horizon (given by (14))

We have the following stocks, respectively, when patch i defects and when all patches cooperate:

$$\bar{x}_i=D_{ii}g\left(\bar{e}_i,\alpha_i\right)+\sum_{j\neq i}D_{ji}g\left(e_j^*,\alpha_j\right);\quad x_i^*=\sum_{j}D_{ji}g\left(e_j^*,\alpha_j\right)$$

We assume that one parameter, $\theta_i=\{p_i,\alpha_i,D_{ii},D_{ij}\}$ or $\theta_j=\{p_j,\alpha_j,D_{ji}\}$, is elevated. We obtain the general following forms for the stocks:

$$\frac{d\bar{x}_i}{d\theta_i}=\frac{\partial\bar{x}_i}{\partial\bar{e}_i}\cdot\frac{\partial\bar{e}_i}{\partial\theta_i}+\frac{\partial\bar{x}_i}{\partial\theta_i}+\sum_{j\neq i}\frac{\partial\bar{x}_i}{\partial e_j^*}\cdot\frac{\partial e_j^*}{\partial\theta_i}\tag{26}$$

$$\frac{d\bar{x}_i}{d\theta_j}=\frac{\partial\bar{x}_i}{\partial\theta_j}+\sum_{l\neq i}\frac{\partial\bar{x}_i}{\partial e_l^*}\cdot\frac{\partial e_l^*}{\partial\theta_j}\tag{27}$$

$$\frac{dx_i^*}{d\theta_i}=\frac{\partial x_i^*}{\partial\theta_i}+\sum_{j}\frac{\partial x_i^*}{\partial e_j^*}\cdot\frac{\partial e_j^*}{\partial\theta_i}\tag{28}$$

$$\frac{dx_i^*}{d\theta_j}=\frac{\partial x_i^*}{\partial\theta_j}+\sum_{l}\frac{\partial x_i^*}{\partial e_l^*}\cdot\frac{\partial e_l^*}{\partial\theta_j}\tag{29}$$

and the residual stock levels

with $g_{\alpha_i^*}\equiv g_{\alpha_i}(e_i^*)$ and $g_{\bar{\alpha}_i}\equiv g_{\bar{\alpha}_i}(\bar{e}_i)$.

A. Impact on the emergence of cooperation

Using Expressions (26) to (29) and Table 1 we compute the following expressions.

Impact of net price, p

Impact of p_i

We first analyze the impact of p_i on concessionaire i's willingness to cooperate by using Expressions (26) to (29) and the table in order to compute the following expression:

Table 2: Computations of derivatives

θ	$\frac{\partial e_i^*}{\partial \theta}$	$\frac{\partial \bar{e}_i}{\partial \theta}$	$\frac{\partial x_i^*}{\partial \theta}$	$\frac{\partial \bar{x}_i}{\partial \theta}$
p_i	$\frac{1-\delta D_{ii} g_{e_i}}{\sum_{j=1}^N \delta D_{ij} p_j g_{e_i e_i}} < 0$	0	0	0
p_j	$-\frac{D_{ij} g_{e_i}}{\sum_{l=1}^N D_{il} p_l g_{e_i e_i}} > 0$	0	0	0
α_i	$-\frac{g_{e_i \alpha_i}}{g_{e_i e_i}} > 0$	$-\frac{g_{e_i \alpha_i}}{g_{e_i e_i}} > 0$	$D_{ii} g_{\alpha_i^*} > 0$	$D_{ii} g_{\bar{\alpha}_i} > 0$
α_j	0	0	$D_{ji} g_{\alpha_j^*} > 0$	$D_{ji} g_{\alpha_j^*} > 0$
D_{ii}	$-\frac{p_i g_{e_i}}{\sum_{j=1}^N D_{ij} p_j g_{e_i e_i}} > 0$	$-\frac{g_{e_i}}{g_{e_i e_i}} > 0$	$g(e_i^*) > 0$	$g(\bar{e}_i) > 0$
D_{ij}	$-\frac{p_j g_{e_i}}{\sum_{j=1}^N D_{ij} p_j g_{e_i e_i}} > 0$	0	0	0
D_{ji}	0	0	$g(e_j^*)$	$g(e_j^*)$

$$\frac{d\left(\Pi_i^c - \Pi_i^d\right)}{dp_i} = \frac{\delta^{kT}}{1-\delta}\left[\delta x_i^* - e_i^* - (1-\delta^{T-1})(\delta \bar{x}_i - \bar{e}_i)\right] + \frac{\delta^{kT} p_i}{1-\delta}\left[\delta \sum_j \frac{\partial x_i^*}{\partial e_j^*}\frac{\partial e_j^*}{\partial p_i} - \frac{\partial e_i^*}{\partial p_i} - \delta(1-\delta^{T-1})\sum_{j\neq i}\frac{\partial \bar{x}_i}{\partial e_j^*}\frac{\partial e_j^*}{\partial p_i}\right]$$

Let us focus on the second term between brackets and rewrite it as follows:

$$\frac{\partial e_i^*}{\partial p_i}\left(\delta \frac{\partial x_i^*}{\partial e_i^*} - 1\right) + \sum_{j\neq i}\frac{\partial e_j^*}{\partial p_i}\left[\delta \frac{\partial x_i^*}{\partial e_j^*} - \delta(1-\delta^{T-1})\frac{\partial \bar{x}_i}{\partial e_j^*}\right] \tag{30}$$

$$\Leftrightarrow \frac{\partial e_i^*}{\partial p_i}\left(\delta D_{ii} g_{e_i^*} - 1\right) + \sum_{j\neq i}\frac{\partial e_j^*}{\partial p_i}\left[\delta D_{ji} g_{e_j^*} - \delta(1-\delta^{T-1}) D_{ji} g_{e_j^*}\right] \tag{31}$$

$$\Leftrightarrow -\frac{\partial e_i^*}{\partial p_i}\left(1 - \delta D_{ii} g_{e_i^*}\right) + \sum_{j\neq i}\frac{\partial e_j^*}{\partial p_i}\delta^T D_{ji} g_{e_j^*} > 0 \tag{32}$$

because we have $\frac{\partial e_i^*}{\partial p_i} < 0$, $1 - \delta D_{ii} g_{e_i^*} > 0$ and $\frac{\partial e_j^*}{\partial p_i} > 0$. Thus, we can conclude that $\frac{d\left(\Pi_i^c - \Pi_i^d\right)}{dp_i} > 0$ if the condition regarding concessionaire i's *willingness-to-cooperate* is satisfied.

This means that an increase in p_i results in an increase in the value of $\frac{d\left(\Pi_i^c-\Pi_i^d\right)}{dp_i}$, thus an increase in the *willingness-to-cooperate*.

Effect of p_j, $j \neq i$

In this case we have

$$\begin{aligned}
\frac{d\left(\Pi_i^c-\Pi_i^d\right)}{dp_j} &= \frac{\delta^{kT}p_i}{1-\delta}\left[\delta\sum_l \frac{\partial x_i^*}{\partial e_l^*}\frac{\partial e_l^*}{\partial p_j} - \frac{\partial e_i^*}{\partial p_j} - \delta(1-\delta^{T-1})\sum_{l\neq i}\frac{\partial \bar{x}_i}{\partial e_l^*}\frac{\partial e_l^*}{\partial p_j}\right] \\
&= \frac{\delta^{kT}p_i}{1-\delta}\left[\frac{\partial e_i^*}{\partial p_j}\left(\delta\frac{\partial x_i^*}{\partial e_i^*}-1\right) + \sum_{l\neq i}\left(\delta\frac{\partial x_i^*}{\partial e_l^*}\frac{\partial e_l^*}{\partial p_j} - \delta(1-\delta^{T-1})\frac{\partial \bar{x}_i}{\partial e_l^*}\frac{\partial e_l^*}{\partial p_j}\right)\right] \\
&= \frac{\delta^{kT}p_i}{1-\delta}\left[-\frac{\partial e_i^*}{\partial p_j}\left(1-\delta D_{ii}g_{e_i^*}\right) + \delta^T\sum_{l\neq i}\frac{\partial e_l^*}{\partial p_j}D_{li}g_{e_l^*}\right] \\
&= \frac{\delta^{kT}p_i}{1-\delta}\left[\underbrace{-\frac{\partial e_i^*}{\partial p_j}\left(1-\delta D_{ii}g_{e_i^*}\right)}_{<0} + \delta^T\left(\underbrace{\frac{\partial e_j^*}{\partial p_j}D_{ji}g_{e_j^*}}_{<0} + \underbrace{\sum_{l\neq i,j}\frac{\partial e_l^*}{\partial p_j}D_{li}g_{e_l^*}}_{>0}\right)\right]
\end{aligned}$$

Using the expressions provided in the table and focusing on the spatial connection between the patch of interest and the patch where the value of the parameter is increased, (i and j), we deduce the following conclusions:

- First, if both dispersal rates D_{ij} and D_{ji} are sufficiently small, then the first and second term between brackets on the RHS of the equality are small, which implies that $\frac{d\left(\Pi_i^c-\Pi_i^d\right)}{dp_j}$ is positive;
  Indeed, when D_{ij} and D_{ji} are small, then $\frac{\partial e_i^*}{\partial p_j}$ and $\frac{\partial e_j^*}{\partial p_j}D_{ji}g_{e_j^*}$ are small. And the sign of the term between brackets (and thus of $\frac{d\left(\Pi_i^c-\Pi_i^d\right)}{dp_j}$) is similar to the sign of $\sum_{l\neq i,j}\frac{\partial e_l^*}{\partial p_j}D_{li}g_{e_l^*}$, which is positive.
- Second, if the degree of spatial connection between the two patches and their own self-retention rate are sufficiently large (or if both patches i and j are weakly spatially-connected with other patches), respectively $D_{ii}+D_{ij}$ and $D_{jj}+D_{ji}$ are sufficiently large, then the term $\sum_{l\neq i,j}\frac{\partial e_l^*}{\partial p_j}D_{li}g_{e_l^*}$ is small, which implies that $\frac{d\left(\Pi_i^c-\Pi_i^d\right)}{dp_j}$ is negative.

Impact of growth, α

Effect of α_i

We analyze the effect of α_i on concessionaire i's willingness to cooperate. We have:

$$\begin{aligned}
\frac{d\left(\Pi_i^c-\Pi_i^d\right)}{d\alpha_i} &= \frac{\delta^{kT}p_i}{1-\delta}\left\{\delta\left(\frac{\partial x_i^*}{\partial\alpha_i}+\frac{\partial x_i^*}{\partial e_i^*}\frac{\partial e_i^*}{\partial\alpha_i}\right)-\frac{\partial e_i^*}{\partial\alpha_i}-(1-\delta^{T-1})\left[\delta\left(\frac{\partial\bar{x}_i}{\partial\alpha_i}+\frac{\partial\bar{x}_i}{\partial\bar{e}_i}\frac{\partial\bar{e}_i}{\partial\alpha_i}\right)-\frac{\partial\bar{e}_i}{\partial\alpha_i}\right]\right\}\\
&= \frac{\delta^{kT}p_i}{1-\delta}\left[\frac{\partial e_i^*}{\partial\alpha_i}\left(\delta D_{ii}g_{e_i^*}-1\right)+\delta D_{ii}g_{\alpha_i^*}-(1-\delta^{T-1})\left(\frac{\partial\bar{e}_i}{\partial\alpha_i}\left(\delta D_{ii}g_{\bar{e}_i}-1\right)+\delta D_{ii}g_{\bar{\alpha}_i}\right)\right]\\
&= \frac{\delta^{kT}p_i}{1-\delta}\left[\frac{\partial e_i^*}{\partial\alpha_i}\left(\delta D_{ii}g_{e_i^*}-1\right)+\delta D_{ii}\left(g_{\alpha_i^*}-(1-\delta^{T-1})g_{\bar{\alpha}_i}\right)\right]
\end{aligned}$$

If D_{ii} is small while $\bar{e}_i>0$, then $\frac{d\left(\Pi_i^c-\Pi_i^d\right)}{d\alpha_i}<0$ and an increase in α_i decreases concessionaire i's incentives to cooperate.

If $D_{ii}=1$, then $1-\delta D_{ii}g_{e_i^*}=0$ and $\frac{d\left(\Pi_i^c-\Pi_i^d\right)}{d\alpha_i}>0$ since $g_{\alpha_i^*}-(1-\delta^{T-1})g_{\bar{\alpha}_i}$ is positive. By a continuity argument, this conclusion remains valid when D_{ii} is sufficiently large.

Effect of α_j, $j\neq i$

We analyze the effect of α_j on concessionaire i's willingness to cooperate. We have:

$$\begin{aligned}
\frac{d\left(\Pi_i^c-\Pi_i^d\right)}{d\alpha_j} &= \frac{\delta^{kT}p_i}{1-\delta}\left[\delta\left(\frac{\partial x_i^*}{\partial\alpha_j}+\frac{\partial x_i^*}{\partial e_j^*}\frac{\partial e_j^*}{\partial\alpha_j}\right)-\delta(1-\delta^{T-1})\left(\frac{\partial\bar{x}_i}{\partial\alpha_j}+\frac{\partial\bar{x}_i}{\partial e_j^*}\frac{\partial e_j^*}{\partial\alpha_j}\right)\right]\\
&= \frac{\delta^{kT+1}p_i}{1-\delta}\left[\delta^{T-1}D_{ji}g_{\alpha_j^*}+\frac{\partial e_j^*}{\partial\alpha_j}\delta^{T-1}D_{ji}g_{e_j^*}\right]\\
&= \frac{\delta^{(k+1)T}p_i}{1-\delta}D_{ji}\left(g_{\alpha_j^*}+g_{e_j^*}\right)>0
\end{aligned}$$

An increase in α_j increases the willingness-to-cooperate of concessionaire i.

Impact of dispersal rate, D

Effect of D_{ii}

We first analyze the effect of the self-retention rate on an concessionaire's willingness to cooperate. We have:

$$\begin{aligned}
\frac{d\left(\Pi_i^c-\Pi_i^d\right)}{dD_{ii}} &= \frac{\delta^{kT}p_i}{1-\delta}\left\{\delta\left(\frac{\partial x_i^*}{\partial D_{ii}}+\frac{\partial x_i^*}{\partial e_i^*}\frac{\partial e_i^*}{\partial D_{ii}}\right)-\frac{\partial e_i^*}{\partial D_{ii}}-(1-\delta^{T-1})\left[\delta\left(\frac{\partial\bar{x}_i}{\partial D_{ii}}+\frac{\partial\bar{x}_i}{\partial\bar{e}_i}\frac{\partial\bar{e}_i}{\partial D_{ii}}\right)-\frac{\partial\bar{e}_i}{\partial D_{ii}}\right]\right\}\\
&= \frac{\delta^{kT}p_i}{1-\delta}\left\{\frac{\partial e_i^*}{\partial D_{ii}}\left(\delta D_{ii}g_{e_i^*}-1\right)+\delta g(e_i^*,\alpha_i)-(1-\delta^{T-1})\left[\frac{\partial\bar{e}_i}{\partial D_{ii}}\left(\delta D_{ii}g_{\bar{e}_i}-1\right)+\delta g(\bar{e}_i,\alpha_i)\right]\right\}\\
&= \frac{\delta^{kT}p_i}{1-\delta}\left(\delta[g(e_i^*,\alpha_i)-g(\bar{e}_i,\alpha_i)]+\delta^T g(\bar{e}_i,\alpha_i)-\left(1-\delta D_{ii}g_{e_i^*}\right)\frac{\partial e_i^*}{\partial D_{ii}}\right).
\end{aligned}$$

The overall effect of D_{ii} on $\Pi_i^c - \Pi_i^d$ is given by the sum of two terms of opposite signs, and is thus ambiguous (due to the expression of $\frac{\partial e_i^*}{\partial D_{ii}}$ provided in the table, when p_i is small we might expect $\frac{d\left(\Pi_i^c - \Pi_i^d\right)}{dD_{ii}}$ to be positive).

Effect of D_{ij}

We now analyze the effect of dispersal from patch i on concessionaire i's willingness to cooperate. We have:

$$\frac{d\left(\Pi_i^c - \Pi_i^d\right)}{dD_{ij}} = \frac{\delta^{kT} p_i}{1-\delta}\left(\delta \frac{\partial x_i^*}{\partial e_i^*}\frac{\partial e_i^*}{\partial D_{ij}} - \frac{\partial e_i^*}{\partial D_{ij}}\right) = -\frac{\delta^{kT} p_i}{1-\delta} \cdot \frac{\partial e_i^*}{\partial D_{ij}}\left(1 - \delta D_{ii} g_{e_i^*}\right) < 0$$

An increase in dispersal from patch i decreases concessionaire i's incentives to cooperate.

Effect of D_{ji}

We finally analyze the effect of dispersal from a given patch *to* patch i on concessionaire i's willingness to cooperate. We have:

$$\begin{aligned}\frac{d\left(\Pi_i^c - \Pi_i^d\right)}{dD_{ji}} &= \frac{\delta^{kT} p_i}{1-\delta}\left[\delta\left(\frac{\partial x_i^*}{\partial D_{ji}} + \frac{\partial x_i^*}{\partial e_j^*}\frac{\partial e_j^*}{\partial D_{ji}}\right) - \delta(1-\delta^{T-1})\left(\frac{\partial \bar{x}_i}{\partial D_{ji}} + \frac{\partial \bar{x}_i}{\partial e_j^*}\frac{\partial e_j^*}{\partial D_{ji}}\right)\right] \\ &= \frac{\delta^{(k+1)T} p_i}{1-\delta}\left[\frac{\partial e_j^*}{\partial D_{ji}} D_{ji} g_{e_j^*} + g(e_j^*, \alpha_j)\right] > 0\end{aligned}$$

An increase in dispersal from patch j *to* patch i increases concessionaire i's incentives to cooperate.

B. Impact on the time threshold, $\bar{T}_i$

Differentiating Condition (14) with respect to parameter θ, we have:

$$\begin{aligned}\frac{d\bar{T}_i}{d\theta} &= \frac{\partial \bar{T}_i}{\partial \theta} + \frac{\partial \bar{T}_i}{\partial \bar{x}_i}\frac{d\bar{x}_i}{d\theta} + \frac{\partial \bar{T}_i}{\partial \bar{e}_i}\frac{\partial \bar{e}_i}{\partial \theta} + \frac{\partial \bar{T}_i}{\partial x_i^*}\frac{dx_i^*}{d\theta} + \frac{\partial \bar{T}_i}{\partial e_i^*}\frac{\partial e_i^*}{\partial \theta} && (33) \\ &= \frac{1}{\ln(\delta)\left[\delta(\bar{x}_i - x_i^*) + e_i^* - \bar{e}_i\right]}\left[\frac{\partial e_i^*}{\partial \theta} - \delta\frac{dx_i^*}{d\theta} + \left(\frac{\delta x_i^* - e_i^*}{\delta \bar{x}_i - \bar{e}_i}\right)\left(\delta\frac{d\bar{x}_i}{d\theta} - \frac{\partial \bar{e}_i}{\partial \theta}\right)\right] && (34)\end{aligned}$$

Since $\delta \in (0,1)$ and $\delta(\bar{x}_i - x_i^*) + e_i^* - \bar{e}_i > 0$, we know that the first term in Equality (34) is always negative. Thus, in order to sign the effect of parameter θ on $\bar{T}_i$ we examine the term between brackets. Using expressions (26)-(29) and Table 1, we check that $\delta\frac{d\bar{x}_i}{d\theta} - \frac{\partial \bar{e}_i}{\partial \theta} \gtrless 0$. Then let us notice that:

$$\begin{aligned}\frac{\partial e_i^*}{\partial \theta} - \delta\frac{dx_i^*}{d\theta} = \frac{\partial e_i^*}{\partial \theta}(1 - \delta D_{ii} g_{e_i^*}) - \delta\left(\frac{\partial x_i^*}{\partial \theta} + \sum_{j\neq i} D_{ji} g_{e_j^*}\frac{\partial e_j^*}{\partial \theta}\right) &< 0 \text{ if } \theta = \{p_i; \alpha_j; D_{ji}\} \\ &> 0 \text{ if } \theta = \{D_{ij}\}\end{aligned}$$

which implies that $\frac{d\bar{T}_i}{d\theta} > 0$ for $\theta = \{p_i; \alpha_j; D_{ji}\}$ and $\frac{d\bar{T}_i}{d\theta} < 0$ for $\theta = \{D_{ij}\}$. By contrast, the sign is ambiguous for $\theta = \{p_j; \alpha_i; D_{ii}\}$. We can yet find some situations highlighting that the overall expression can be positive or negative. We focus on the expression between brackets in Condition (34).

Effect of p_j, $j \neq i$

$$\frac{\partial e_i^*}{\partial p_j}\left(1-\delta\frac{\partial x_i^*}{\partial e_i^*}\right)-\delta\sum_{l\neq i}\frac{\partial x_i^*}{\partial e_l^*}\frac{\partial e_l^*}{\partial p_j}+\delta\left(\frac{\delta x_i^*-e_i^*}{\delta\bar{x}_i-\bar{e}_i}\right)\sum_{l\neq i}\frac{\partial\bar{x}_i}{\partial e_l^*}\frac{\partial e_l^*}{\partial p_j} \tag{35}$$

$$\Leftrightarrow \frac{\partial e_i^*}{\partial p_j}(1-\delta D_{ii}g_{e_i})+\delta\sum_{l\neq i}D_{li}g_{e_l}\frac{\partial e_l^*}{\partial p_j}\left(\frac{\delta(x_i^*-\bar{x}_i)-e_i^*+\bar{e}_i}{\delta\bar{x}_i-\bar{e}_i}\right) \tag{36}$$

$$\Leftrightarrow \frac{\partial e_i^*}{\partial p_j}(1-\delta D_{ii}g_{e_i})+\delta\left(\frac{\delta(x_i^*-\bar{x}_i)-e_i^*+\bar{e}_i}{\delta\bar{x}_i-\bar{e}_i}\right)\left(D_{ji}g_{e_j}\frac{\partial e_j^*}{\partial p_j}+\sum_{l\neq i,j}D_{li}g_{e_l}\frac{\partial e_l^*}{\partial p_j}\right) \tag{37}$$

Using the expressions provided in the table, we can obtain conclusions that highlight that the effect on $\bar{T}_i$ depends on the dispersal process.

- First, if D_{ij} is small enough, then expression (36) is negative, which implies that the value of $\bar{T}_i$ increases when p_j increases;
- Second, if D_{ji} and $\sum_{l\neq i,j} D_{li}D_{lj}$ are small enough, then expression (36) is positive, which implies that the value of $\bar{T}_i$ decreases when p_j increases.
  Indeed, this leads to a small value of the last term between brackets, $D_{ji}g_{e_j}\frac{\partial e_j^*}{\partial p_j}+\sum_{l\neq i,j} D_{li}g_{e_l}\frac{\partial e_l^*}{\partial p_j}$. Thus, the sign of $\frac{d\bar{T}_i}{dp_j}$ depends only on that of $\frac{\partial e_i^*}{\partial p_j}(1-\delta D_{ii}g_{e_i})$, which is positive. We thus conclude that $\frac{\partial \bar{T}_i}{\partial p_j}$ is negative.

Effect of α_i

$$\frac{\partial e_i^*}{\partial \alpha_i}\left(1-\delta\frac{\partial x_i^*}{\partial e_i^*}\right)-\delta\frac{\partial x_i^*}{\partial \alpha_i}+\left(\frac{\delta x_i^*-e_i^*}{\delta\bar{x}_i-\bar{e}_i}\right)\left[\delta\left(\frac{\partial\bar{x}_i}{\partial\alpha_i}+\frac{\partial\bar{x}_i}{\partial\bar{e}_i}\frac{\partial\bar{e}_i}{\partial\alpha_i}\right)-\frac{\partial\bar{e}_i}{\partial\alpha_i}\right] \tag{38}$$

$$\Leftrightarrow \frac{\partial e_i^*}{\partial \alpha_i}\left(1-\delta D_{ii}g_{e_i^*}\right)-\delta D_{ii}\left[g_{\alpha_i^*}-g_{\bar{\alpha}_i}\left(\frac{\delta x_i^*-e_i^*}{\delta\bar{x}_i-\bar{e}_i}\right)\right] \tag{39}$$

So, if δD_{ii} is sufficiently small while $\bar{e}_i$ remains positive, then the sign of (37) is positive, which implies that $\bar{T}_i$ would decrease when the growth-related parameter increases in patch i.

Effect of D_{ii}

$$\frac{\partial e_i^*}{\partial D_{ii}}\left(1-\delta\frac{\partial x_i^*}{\partial e_i^*}\right)-\delta\frac{\partial x_i^*}{\partial D_{ii}}+\left(\frac{\delta x_i^*-e_i^*}{\delta\bar{x}_i-\bar{e}_i}\right)\left[\delta\left(\frac{\partial\bar{x}_i}{\partial D_{ii}}+\frac{\partial\bar{x}_i}{\partial\bar{e}_i}\frac{\partial\bar{e}_i}{\partial D_{ii}}\right)-\frac{\partial\bar{e}_i}{\partial D_{ii}}\right]$$

$$\Leftrightarrow \frac{\partial e_i^*}{\partial D_{ii}}\left(1-\delta D_{ii}g_{e_i^*}\right)-\delta g(e_i^*,\alpha_i)+\left(\frac{\delta x_i^*-e_i^*}{\delta\bar{x}_i-\bar{e}_i}\right)\left[\delta g(\bar{e}_i,\alpha_i)+\frac{\partial\bar{e}_i}{\partial D_{ii}}\left(\delta D_{ii}g_{\bar{e}_i}-1\right)\right]$$

$$\Leftrightarrow \frac{\partial e_i^*}{\partial D_{ii}}\left(1-\delta D_{ii}g_{e_i^*}\right)-\delta\underbrace{\left[g(e_i^*,\alpha_i)-\left(\frac{\delta x_i^*-e_i^*}{\delta\bar{x}_i-\bar{e}_i}\right)g(\bar{e}_i,\alpha_i)\right]}_{>0}$$

We obtain a conclusion in one case described as follows. If δ is sufficiently small (so that $\frac{\partial e_i^*}{\partial D_{ii}}\left(1-\delta D_{ii} g_{e_i^*}\right) > \delta\left[g(e_i^*,\alpha_i) - \left(\frac{\delta x_i^* - e_i^*}{\delta \bar{x}_i - \bar{e}_i}\right) g(\bar{e}_i,\alpha_i)\right]$) while $\bar{e}_i$ remains positive, then the sign of the expression is that of $\frac{\partial e_i^*}{\partial D_{ii}}$, which is positive.

The scope of applicability of trigger strategies

Concessionaires implementing trigger strategies will not get renewed at the end of the tenure block where punishment is implemented. This is a form of self-punishment, which can be seen as an additional incentive scheme.[29] Yet it is difficult to think about the frequent use of self-punishment schemes in the real-world, so we only briefly consider this possibility.

Proposition 9. *When concessionaires follow trigger strategies, cooperation will emerge as an equilibrium outcome if and only if the following condition holds (for any concessionaire i):*

$$\delta x_i^* - e_i^* - (1-\delta^{T-1})\left[\delta \bar{\bar{x}}_i - \bar{e}_i\right] > 0,$$

where $\bar{\bar{x}}_i = \sum_j D_{ji} g(\bar{e_j}) > \bar{e}_i > 0$.

Proof. If concessionaire i deviates during tenure $k+1$ (while other concessionaires follow trigger strategies) then this concessionaire's payoff is Π_i^d, where :

$$p_i\left[x_{i0} - e_i^* + \frac{\delta(1-\delta^{kT})}{1-\delta}(x_i^* - e_i^*) + \delta^{kT}(e_i^* - \bar{e}_i) + \frac{\delta^{kT+1}(1-\delta^{T-1})}{1-\delta}\left(\bar{\bar{x}}_i - \bar{e}_i\right) + \delta^{(k+1)T-1}\bar{e}_i\right].$$

Now, computing the difference $\Pi_i^c - \Pi_i^d$, we obtain:

$$\begin{aligned}
\Pi_i^c - \Pi_i^d &= p_i\left[\frac{\delta^{kT+1}}{1-\delta}(x_i^* - e_i^*) - \delta^{kT}(e_i^* - \bar{e}_i) - \frac{\delta^{kT+1}(1-\delta^{T-1})}{1-\delta}\left(\bar{\bar{x}}_i - \bar{e}_i\right) - \delta^{(k+1)T-1}(1-\delta)\bar{e}_i\right] \\
&= \frac{p_i}{1-\delta}\left[\delta^{kT+1}x_i^* - \delta^{kT}e_i^* + \delta^{kT}(1-\delta^{T-1})\bar{e}_i - \delta^{kT}(1-\delta^{T-1})\delta\bar{\bar{x}}_i\right] \\
&= \delta^{kT}\frac{p_i}{1-\delta}\left[\delta x_i^* - e_i^* - (1-\delta^{T-1})\left(\delta\bar{\bar{x}}_i - \bar{e}_i\right)\right].
\end{aligned}$$

The conclusion follows from this equality. Condition $\bar{\bar{x}}_i = \sum_j D_{ji} g(\bar{e_j}) > \bar{e}_i$ follows from the same argument than in the proof of Proposition 1. ☐

The proof confirms one of our previous claims regarding the incentives to defect: it is intuitive and straightforward to show that incentives to defect are the same at any given period, that is, they are not time dependent. This proposition implies that the incentives to defect increase with a longer time horizon.[30] Moreover, the inequality characterizing the scope of trigger strategies is less restrictive than the similar condition in Proposition 3. Thus, using trigger strategies in addition to the concession instrument enlarges the scope for full cooperation.

[29] It is useful to recall that the instrument analyzed here does not require that the concessionaires use such kind of self-punishment devices in order to induce efficient resource management.

[30] This conclusion follows if we differentiate the expression of the difference between payoffs as a function of the time horizon.

Robustness to stock-dependent costs

We state the equivalent of Propositions 1 and 3 for the case of stock-dependent marginal costs, and we provide the corresponding proofs.[31]

Proposition 10. *The optimal defection strategy of concessionaire i in tenure block k is given by:*

$$\bar{e}_{ikT-1} = c_i^{-1}(p_i)$$

and, for any period $(k-1)T \leq t \leq kT-2$, we have $\bar{e}_{it} = \bar{e}_i > 0$ where:

$$\delta D_{ii} g_i'(\bar{e}_i)\left(p_i - c_i(\bar{x}_{it+1})\right) = p_i - c_i(\bar{e}_{it}) \quad \textit{with} \quad \bar{x}_{it} > \bar{e}_{it}.$$

Indeed $\bar{e}_{it} = \bar{e}_i$ since the system of optimality conditions is time and state independent.

Proof. We proceed by backward induction. At final period $kT-1$, concessionaire i's problem is to maximize

$$\max_{e_{ikT-1} \geq 0} p_i\left(x_{ikT-1} - e_{ikT-1}\right) - \int_{e_{ikT-1}}^{x_{ikT-1}} c_i(s)ds$$

Using the first order condition enables us to conclude immediately that $c_i(\bar{e}_{ikT-1}) = p_i$, that is, concessionaire i extracts the stock up to level $\bar{e}_{ikT-1} = c_i^{-1}(p_i)$. Now, moving backward, at period $T-2$, this concessionaire's problem becomes:

$$\max_{e_{ikT-2} \geq 0} p_i\left[x_{ikT-2} - e_{ikT-2}\right] - \int_{e_{ikT-2}}^{x_{ikT-2}} c_i(s)ds + \delta p_i \left(\sum_{j \neq i} D_{ji} g(\bar{e}_{jkT-2}) + D_{ii} g(\bar{e}_{ikT-2}) - \bar{e}_{ikT-1}\right)$$

$$-\delta \int_{\bar{e}_{ikT-1}}^{\sum_{j\neq i} D_{ji} g(\bar{e}_{jkT-2}) + D_{ii} g(\bar{e}_{ikT-2})} c_i(s)ds.$$

Using the first order condition (with respect to $\bar{e}_{ikT-2}$) and $\bar{e}_{ikT-1} = c_i^{-1}(p_i)$, we obtain that $\bar{e}_{ikT-2}$ is characterized by the following condition:

$$\delta D_{ii} g'(\bar{e}_{ikT-2})\left(p_i - c_i(\sum_{j \neq i} D_{ji} g(\bar{e}_{jkT-2}) + D_{ii} g(\bar{e}_{ikT-2}))\right) = p_i - c_i(\bar{e}_{ikT-2}).$$

This optimality condition enables quickly to deduce, since economic returns and spatial parameters are time independent, that $\bar{e}_{ikT-2}$ depends only on $\bar{e}_{jkT-2}$ $(j \neq i)$ and not on $\bar{x}_{lkT-2}$ $(l \in I)$. This implies that $\bar{e}_{ikT-2}$ is time and state independent. Repeating the same argument of backward induction, it is easily checked that any residual stock level $\bar{e}_{it}$ (where $(k-1)T \leq t \leq kT-3$) is characterized by the same optimality condition. This concludes the proof. □

Finally, we have:

[31] To keep the exposition as simple and short as possible, we here focus on the case of an interior optimal defection strategy. In Proposition 1 this corresponds to the case where the value of $g_i'(0)$ is high.

Proposition 11. *Complete cooperation emerges as an equilibrium outcome if and only if, for any concessionaire i, the following condition holds:*

$$\frac{\delta^{kT+1}}{1-\delta}\left[p_i\left(x_i^*-e_i^*\right)-\int_{e_i^*}^{x_i^*}c_i(s)ds\right]-\delta^{kT}\left[p_i\left(e_i^*-\bar{e}_i\right)-\int_{\bar{e}_i}^{e_i^*}c_i(s)ds\right]$$

$$-\frac{\delta^{kT+1}(1-\delta^{T-1})}{1-\delta}\left[p_i\left(\bar{x}_i-\bar{e}_i\right)-\int_{\bar{e}_i}^{\bar{x}_i}c_i(s)ds\right]-\delta^{(k+1)T-1}\left[p_i\left(\bar{e}_i-c_i^{-1}(p_i)\right)-\int_{c_i^{-1}(p_i)}^{\bar{e}_i}c_i(s)ds\right]>0. \tag{40}$$

Proof. If concessionaire i deviates during tenure $k+1$ (while other concessionaires follow their candidate equilibrium strategies) then this concessionaire's payoff is :

$$\Pi_i^d=p_i\left[x_{i0}-e_i^*\right]-\int_{e_i^*}^{x_{i0}}c_i(s)ds+\frac{\delta(1-\delta^{kT})}{1-\delta}\left[p_i\left(x_i^*-e_i^*\right)-\int_{e_i^*}^{x_i^*}c_i(s)ds\right]$$
$$+\delta^{kT}\left[p_i\left(e_i^*-\bar{e}_i\right)-\int_{\bar{e}_i}^{e_i^*}c_i(s)ds\right]+\frac{\delta^{kT+1}(1-\delta^{T-1})}{1-\delta}\left[p_i\left(\bar{x}_i-\bar{e}_i\right)-\int_{\bar{e}_i}^{\bar{x}_i}c_i(s)ds\right]$$
$$+\delta^{(k+1)T-1}\left[p_i\left(\bar{e}_i-c_i^{-1}(p_i)\right)-\int_{c_i^{-1}(p_i)}^{\bar{e}_i}c_i(s)ds\right].$$

Now we can compute $\Pi_i^c-\Pi_i^d=B$, with:

$$B=\frac{\delta^{kT+1}}{1-\delta}\left[p_i\left(x_i^*-e_i^*\right)-\int_{e_i^*}^{x_i^*}c_i(s)ds\right]-\delta^{kT}\left[p_i\left(e_i^*-\bar{e}_i\right)-\int_{\bar{e}_i}^{e_i^*}c_i(s)ds\right]$$

$$-\frac{\delta^{kT+1}(1-\delta^{T-1})}{1-\delta}\left[p_i\left(\bar{x}_i-\bar{e}_i\right)-\int_{\bar{e}_i}^{\bar{x}_i}c_i(s)ds\right]-\delta^{(k+1)T-1}\left[p_i\left(\bar{e}_i-c_i^{-1}(p_i)\right)-\int_{c_i^{-1}(p_i)}^{\bar{e}_i}c_i(s)ds\right]. \tag{41}$$

The conclusion follows from Equality (41). □