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« Spatial concessions with limited  
tenure »

Nicolas QUEROU  
Agnès TOMINI  
Christopher COSTELLO

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Unité de Formation et de Recherche d'Economie  
Avenue Raymond DUGRAND C.S. 79606  
34 960 MONTPELLIER Cedex 2

E-mail : lameta@lameta.univ-montp1.fr  
montp1.fr



Université Montpellier 1



Ecole Nationale Supérieure Agronomique



CENTRE NATIONAL  
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# Spatial concessions with limited tenure

Nicolas Quérou,\* Agnes Tomini,† and Christopher Costello‡

## Abstract

We examine theoretically a system of spatially-connected natural resource concessions with limited tenure. The resource migrates around the system and thus induces a spatial externality, so complete decentralization 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; natural resources; spatial externalities; dynamic games

## 1 Introduction

Diverse forms of property rights are increasingly employed to help overcome the tragedy of the commons in natural resource use. Because governments are usually unable or unwilling to relinquish all control to private owners, limited-duration “concessions,” where property rights are allocated for a fixed duration, have been implemented in many countries to manage myriad resources (Costello and Kaffine (2008)). This system grants rights to exploit the resource for a determined period of time to a concessionaire, who is typically free to choose how to manage the resource during the tenure period. While these concessions are commonly awarded over a specific geographical area, there is mounting scientific evidence that many natural resources previously thought of as *aspatial* are in fact mobile: fish swim,

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\*CNRS, UMR5474 LAMETA, F-34000 Montpellier, France. E-mail: querou@supagro.inra.fr

†Aix-Marseille University (Aix-Marseille School of Economics): CNRS & EHESS, Centre de la Vieille Charité, 2 rue de la charité, F-13002, Marseille, France. E-mail: agnestomini@gmail.fr

‡Bren School, UCSB and NBER. E-mail: costello@bren.ucsb.edu

birds migrate, pollen drifts, and water flows. This movement of the resource stock induces an externality and calls into question the ability of spatially allocated concessions to appropriately address the tragedy of the commons. Here, we analyze whether concessions can be used within a system of spatial property rights to correct spatial externalities that are pervasive for mobile natural resources.

Concessions are used in various sectors of the economy, including infrastructure, construction, and extractive industries; they feature prominently in natural resource settings such as oil, gas, minerals, forests, and fisheries (Manh Hung et al. 2006; Karsenti et al. 2008; Smith et al. 2003). Previous authors have focused on features of concession contracts such as the specific design of concession agreements (Dasgupta et al. (1999), Leffler and Rucker (1991)), the awarding process (Klein (1998)) and the choice of royalties (or fees) for extraction rights (Gray (2000), Hardner and Rice (2000), Vincent (1990), Giudice et al. (2012)), and issues of imperfect enforcement (Guasch et al. (2004)). But this literature is often agnostic about the sector being managed. A more focused literature specifically addresses the use of concessions for natural resource management. Vincent (1990) emphasizes the failure of royalty systems because of undervaluation, and analyzes how the inefficiency of this system affects forest management. Kolstad and Soreide (2009) and Amacher et al. (2012) analyze how corruption impacts key features of concessions, from the awarding process to royalties rates, land size, or forest logging. Amacher et al. (2001), Clarke et al. (1993) and Smith et al. (2003) analyze illegal exploitation within forest concessions, and finally Barbier and Burgess (2001) focus on tenure insecurity.

In this paper, we build on this foundation by focusing 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. Indeed, the spatial mobility of natural resources may challenge incentives for efficient resource use, since part of the resource left *in situ* may disperse elsewhere, which implies that the resource stock will now depend on strategic decisions of adjacent owners. This is a feature shared by many resources: game, waterfowl, forest due to migratory processes (e.g., Albers (1996)), or fire movement (e.g., Konoshima et al. (2008)), or even water because of the existence of flux processes (e.g., Brozovic et al. (2010)).

A central characteristic of our analysis is the assignment of spatial property rights, which is an issue with great contemporary policy appeal, which has given rise to a large and quickly growing literature.<sup>1</sup> Many natural resources management approaches have spatial features. Forests, game, waterfowl, and water are some of the terrestrial examples of resources governed and extracted by pri-

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<sup>1</sup>Wilen et al. (2012) provides an informative review of spatial property rights in fisheries.

vate owners who possess some degree of spatial ownership over the resource stock. Even in the ocean, which has traditionally been viewed as non-excludable, spatial property rights are emerging. For example, the Chilean coast contains over 700 territorial user right fisheries (TURFs) where firms manage and extract fishery resources in a spatial property rights system (Wilén et al. 2012); more broadly 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). Resource mobility entails spatial externalities since harvest in one patch-area inherently affects harvests, and thus incentives, in other patch-areas. While various spatial property rights systems are employed to manage a wide array of resources, the fishery is perhaps the best example of a resource for which property rights will lead to spatial externalities. The economics literature in this context is growing (see Kapaun and Quaas (2013) and Costello et al. (2015) for recent contributions) but analyses on concessions are scarce. An exception is Costello and Kaffine (2008) who explore the effects of limited-tenure property rights for a single, aspatial resource. They find that limiting tenure weakens the incentive to steward one's own resource, but that fully efficient extraction may still be possible under this weakened right. But because they did not consider the possibility of resource mobility or multiple spatially connected concessions, spatial externalities were absent, so they could not examine the effects of limited tenure on efficiency for the class of resources considered here.

Despite the apparent ubiquity with which limited-duration concessions are used to manage spatial natural resources, this issue has never been addressed by economists. To the best of our knowledge, this is the first paper to analyze the design of limited-tenure concessions in a spatial property rights system. The well-studied spatially-connected concessions used to manage fisheries on the Pacific coast of Baja California, Mexico are expanding: In 2000, a 10th TURF was granted to several cooperatives for a 20 year duration with the possibility of renewal. The EU Commission has suggested introducing Transferable Fishing Concessions (TFCs) under which limited user rights are granted to exploit the mobile resources. McCay et al. (2014) examine a case study from the Pacific coast of Mexico, where a community-oriented fisheries management has been implemented based on fish species concessions. For instance, each cooperative has exclusive access and user rights to certain species like abalone, lobster or turban snail. And in 2011, the government of Indonesia implemented a moratorium on new forest concessions in an attempt to pursue other resource management reforms. Thus, while common around the world for myriad resources, important policy decisions regarding spatial concessions are being made with little input from economic theory. An applied contribution of our work is to help inform that policy discussion.

Our analysis is entirely theoretical, but is focused on contributing to key con-

temporary 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. Precisely owing to the spatial connections, each owner's extraction imposes an externality on the other owners. On the flip side, an owner's conservation efforts spill over to other owners; no owner is a sole residual claimant of his conservation behavior. Thus, spatial connectivity weakens property rights and suggests that each owner will extract the resource at too-rapid a rate. To make matters worse, if production functions or spillovers are spatially heterogeneous, then the socially-optimal level of extraction will differ across space. Kaffine and Costello (2011) noted this externality and suggested a private "unitization" instrument to correct the market failure. The theoretical idea was for profit sharing to induce all owners to cooperate over spatial extraction; they showed that following this instrument could induce first-best harvesting behavior among all owners. While it is theoretically attractive, and helps to frame the challenge of coordinating spatial property owners, its application to real-world resource conflict is limited because: (1) It requires *all* property owners to be aware of the full spatial and economic dynamics of the entire system, (2) It requires the resource manager to devolve all management responsibility, in perpetuity, to the spatial property rights holders, (3) it requires the sharing of profit (not revenue), which may be costly to credibly measure, and (4) It requires all harvesters to contribute 100% of profits to a common pool, which is later redistributed based on property-specific characteristics. Furthermore, while some profit-sharing arrangements have been observed empirically, concessions are much more commonly used. In this paper we propose a simple limited-tenure concession instrument that aims to achieve economically-efficient spatial resource use and overcome the limitations noted above.

The instrument we propose involves assigning limited-duration tenure of each patch to a private concessionaire. Under this set of spatial concessions with limited tenure, each concessionaire then faces an interesting, and to our knowledge unexplored, set of incentives. At first glance the instrument we propose would seem to exacerbate the problem. First, the spatial externality has not been internalized, so each concessionaire will have a tendency to overexploit the resource. Second, the limited-duration tenure induces each concessionaire to extract the resource more rapidly than is socially optimal so as to extract the rents prior to the terminal date of his tenure. Both incentives appear to work in the wrong direction, leading to excessive harvest rates in all patches, which is socially inefficient.

To counteract this tendency toward overharvest, we implement two refinements commonly observed in real concession contracts; these dramatically alter the incentives of the concessionaires. First, the regulator will announce for each patch a "minimum stock," below which the concessionaire should never harvest. Second,

the regulator commits to renewing the concession of any concessionaire who adheres to the minimum stock requirement every period. Indeed, this is a stylized version of how many concessions are implemented in practice.<sup>2</sup> If the concessionaire maintains the stock above the (pre-announced) minimum level for the duration of his tenure, his tenure will be renewed for another tenure block. If not, he loses his concession and it is allocated to another user.

Under this setup, a concessionaire must decide whether to comply with the minimum stock requirement (in which case he cannot extract as much profit under the current tenure block, but he is assured of retaining ownership over multiple tenure blocks) or to defect (and harvest in way that maximizes his profit over the current tenure block only). Naturally, because the patches are interconnected, the payoffs under either strategy will depend on the strategy adopted by the other concessionaires. Thus, this system represents a spatial-temporal game.

Despite the complexity of this setup, we are able to derive explicit, analytically tractable results. 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). Importantly, the regulator in this setup has only loose control over the actual harvest achieved in each patch. She chooses only the minimum stock announced for each patch and the tenure length. There we find an interesting, and somewhat counterintuitive result. We show that longer (not shorter) tenure is more likely to lead to defection from the efficient harvest rate. This odd result 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. Among other features, they 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. Our model also has these features, but all under the umbrella of strategic interactions owing to the mobility of the resource. Thus, in our setting, 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. In the extreme (with infinite-duration tenure), the concessionaire has *no* incentive to abide by the minimum stock requirement. Through this logic, we can show that for sufficiently long (but still finite) tenure length, concessionaires will always have incentives to defect; thus tenure must not

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<sup>2</sup>For example, many forest concessions contain environmental provisions that, if violated, render the concessionaire ineligible for future concessions. And the TURF systems in Mexico and Chile contain maximum harvest provisions, whose adherence is required for renewal.

be too long.

Overall, we find that while strong (i.e. perpetual) property rights will not lead to socially efficient resource use in spatially-connected systems, it will often be possible to design limited-tenure property rights that will. The basic intuition is to induce private owners to adhere to socially-optimal resource extraction rates by promising renewed tenure if and only if they adhere to these guidelines. Under certain circumstances, even this will not be a sufficient incentive because the gap between what a private owner can capture through rapid overexploitation, and what he can gain through a low extraction rate (even into perpetuity), is just too great. In what follows we also consider a number of possible extensions, including the application of trigger strategies to further induce cooperation.

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 5 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 in this paper.

### 2.1 The model

We follow the basic setup of Kaffine and Costello (2011) and Costello et al. (2015) where a natural resource stock (denoted by  $x$ ) 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. The resource is mobile and can migrate around this system. In particular, denote by  $D_{ij} \geq 0$  the fraction of the resource stock in patch  $i$  that migrates to patch  $j$  in a single time period. Since some fraction of the

resource may indeed flow out of the system entirely, the dispersal fractions need not sum to one:  $\sum_i D_{ji} \leq 1$ .<sup>3</sup>

The resource may grow, and the growth conditions may be patch-specific denoted by the parameter  $\alpha_j$ . This patch-specific parameter reflects resource growth and has many possible interpretations including intrinsic rate of growth, carrying capacity, and the sheer size of the patch. Assimilating all of this information, the equation of motion in patch  $i$ , in the absence of harvest, is given as follows:

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

Here  $g(x_{jt}, \alpha_j)$  is the period- $t$  production in patch  $j$ . Following the literature, we require that  $\frac{\partial g(x, \alpha)}{\partial x} > 0$ ,  $\frac{\partial g(x, \alpha)}{\partial \alpha} > 0$ ,  $\frac{\partial^2 g(x, \alpha)}{\partial x^2} < 0$ , and  $\frac{\partial^2 g(x, \alpha)}{\partial x \partial \alpha} > 0$ . We also assume that extinction is absorbing,  $g(0; \alpha_j) = 0$ , and that the growth rate is finite,  $\frac{\partial g(x, \alpha)}{\partial x} \Big|_{x=0} < \infty$ .<sup>4</sup> All standard biological production functions are special cases of  $g(x, \alpha)$ .

Harvest in patch  $i$ , period  $t$  is given by  $h_{it}$  and we follow the literature by defining the *residual stock*, or *escapement*, left for reproduction which is given by  $e_{it} \equiv x_{it} - h_{it}$ . This gives rise to the patch- $i$  equation of motion as follows:

$$x_{it+1} = \sum_{j=1}^N D_{ji} g_j(e_{jt}). \quad (2)$$

Thus, the timing of the process is as follows: In the beginning of period  $t$  the resource stock is observed. Harvest then takes place (resulting in residual stock levels  $e_{it}$  for any patch  $i$ ), and the residual stock grows and disperses across the spatial domain: some fraction stays within patch  $i$ , and some flows to other patches. By the identity  $e_{it} \equiv x_{it} - h_{it}$ , there is a duality between choosing *harvest* and choosing *residual stock* as the decision variable. We use residual stock because it turns out to overcome many technical issues that arise when one uses harvest

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<sup>3</sup>This follows the recent literature from the natural sciences (see, e.g., Nathan et al. (2002), or Siegel et al. (2003)) who model dispersal of passive ‘‘Lagrangian particles.’’ An endogenous dispersion parameter may be a relevant alternative to account for density-dependent dispersal processes, or situations where agents can affect that process. While this has appeal in some settings, we focus instead on the potential performance of the described instrument. Moreover, we believe that this alternative assumption is unlikely to change the main qualitative results of our study.

<sup>4</sup>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  $g'_i(x)$  and  $g''_i(x)$  instead of (respectively)  $\frac{\partial g(x, \alpha_i)}{\partial x}$  and  $\frac{\partial^2 g(x, \alpha_i)}{\partial x^2}$  in most parts of the paper.

as the decision variable (though the two are formally identical).<sup>5</sup> Specifically, by adopting residual stock as the control, we are able to fully characterize the optimal policy (in both centralized and decentralized cases); one can then back out the optimal harvest.

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  $p_i$ .<sup>6</sup> Profit in patch  $i$ , time  $t$  is given by:

$$\Pi_{it} = p_i (x_{it} - e_{it}). \quad (3)$$

We will employ this framework to compare the outcome and welfare implications of three different property right systems: (1) a benevolent social planner who seeks to maximize aggregate social welfare, (2) a set of decentralized and non-cooperative property rights owners, and (3) the same set of property right owners who operate in a limited-tenure concession system we propose here.

### 2.1.1 Social Planner's Problem

We begin with the social planner who must solve the complicated problem of choosing the optimal spatial and temporal pattern of harvest to maximize the net present value of profit across the entire domain given the discount factor  $\delta$ . The planner's objective is:

$$\max_{\{e_{1t}, \dots, e_{Nt}\}} \sum_{t=0}^{\infty} \sum_{i=1}^N \delta^t p_i (x_{it} - e_{it}), \quad (4)$$

subject to the equation of motion (2) for each patch  $i = 1, 2, \dots, N$ . Somewhat surprisingly, this complicated spatial optimization problem has a tractable solution. Focusing on interior solutions, in any patch  $i$ , the planner should achieve a residual stock level as follows:

$$g'_i(e_{it}^*) = \frac{p_i}{\delta \sum_j D_{ij} p_j} \quad (5)$$

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  $t$ :

$$e_{it}^* = e_i^*. \quad (6)$$

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<sup>5</sup>This mathematical convenience was pointed out in Reed (1979) and has been adopted by several subsequent contributions (Costello and Polasky (2008), Kapaun and Quaas (2013) among others).

<sup>6</sup>This assumption is widely adopted in the mainstream literature, 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). Moreover, we discuss in section 4.3 the robustness of the instrument for the case of stock-dependent costs.

Since biological growth, dispersal, and economic returns are patch-specific, the optimal policy will vary across patches.

### 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. We assume that the owner of patch  $i$  makes her own decisions about harvest in patch  $i$ , with complete information about the stock, growth characteristics, and economic conditions present throughout the system. In that case owner  $i$  solves:

$$\max_{\{e_{it}\}} \sum_{t=0}^{\infty} \delta^t p_i (x_{it} - e_{it}). \quad (7)$$

subject to the equation of motion (2). Naturally, because owner  $i$ 's stock,  $x_{it+1}$ , depends on owner  $j$ 's residual stock,  $e_{jt}$ , this induces a game across the  $N$  players. Kaffine and Costello (2011) solve for the subgame perfect Nash equilibrium of this game by analytical backward induction on the Bellman equation for each owner  $i$ , and prove (in their lemma 1) that, at a given period  $t$ , owner  $i$  will always harvest down to a residual stock level  $\bar{e}_{it}$  that satisfies:

$$g'_i(\bar{e}_{it}) = \frac{1}{\delta D_{ii}} \quad (8)$$

It is a straightforward matter 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 (8) implies that  $\bar{e}_{it} = \bar{e}_i$  for any time period.<sup>7</sup> In order to make the exposition of our results as simple as possible, we rule out corner solutions (cases where the entire stock is harvested or where there is no harvest).<sup>8</sup>

### 2.1.3 Decentralized, Limited-Tenure Property Rights

The final regime, and the one we focus on in this paper, is similar to the perpetual property rights case above, except that the property rights are of limited duration. Under this regime, 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.” All concessionaires have the possibility of renewal for a second tenure block, a third tenure block, and so forth. Indeed, it is the possibility of renewal that will ultimately

<sup>7</sup>This result actually implies that the open loop and feedback control rules are identical.

<sup>8</sup>Technically, this is equivalent to assuming lower-bound conditions on marginal growth  $g_i(0)$  when stock nears exhaustion and an upper-bound condition when there is no harvest.

incentivize the concessionaire to deviate from her privately-optimal harvest rate; this fact may be leveraged to induce efficient outcomes.

The instrument is designed as follows. At  $t = 0$  the regulator offers to concessionaire  $i$  a contract, which consists of two parameters: (1) A “target stock,”  $\mathcal{S}_i$ , below which the concessionaire must never harvest and (2) 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 target stock condition has been met every period. Because  $e_{it} \leq x_{it}$ , this rule implies that concession  $i$  will be renewed if and only if:

$$e_{it} \geq \mathcal{S}_i \quad \forall t \leq \mathcal{T}_i - 1 \quad (9)$$

This setup confers a great deal of autonomy to the concessionaire - in every period she is free to choose any harvest level that suits her. The regulator’s challenge is to determine a set of target stocks  $\{\mathcal{S}_1, \mathcal{S}_2, \dots, \mathcal{S}_N\}$  and tenure lengths  $\{\mathcal{T}_1, \mathcal{T}_2, \dots, \mathcal{T}_N\}$  (i.e., a  $\{\mathcal{S}_i, \mathcal{T}_i\}$  pair to offer each concessionaire) that will incentivize all concessionaires to simultaneously, and in every period, deliver the socially optimal level of harvest in all patches.

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. Our proposed instrument is as follows:

**Definition 1.** *The Limited-Tenure Spatial Concession Instrument is defined by  $\mathcal{S}_i$  and  $\mathcal{T}_i = T \forall i$ , where  $T$  is a fixed positive integer which we will derive below.*<sup>9</sup>

The focus of our study is to highlight that spatial limited-tenure concessions, if implemented with care, can be used to induce agents to manage resources efficiently. As such, we assume that the only role of the regulator or resource manager is to monitor and renew concessions. In particular, we do not consider explicitly the regulator’s potential incentives in offering concessions.

Agents may, or may not, comply with the terms of the instrument. 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 infinite (albeit discounted) income stream. 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

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<sup>9</sup>Intuitively, since agents are heterogeneous, tenure lengths could well 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 agents’ incentives to cooperate. This characterization is provided by expression 16 in Section 3.

(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.<sup>10</sup>

## 2.2 Cooperation vs. Defection

We want to derive the conditions under which the socially optimal policies emerge as Nash equilibrium outcome (as in Kaffine and Costello (2011), the open loop and feedback control rules are identical here). First, to analyze the tradeoff between cooperation and defection for concessionaire  $i$ , we compute the payoffs that each agent could achieve under both scenarios, and we characterize the optimal defection strategies that could be pursued by any concessionaire.

We first assume that all  $N$  concessionaires cooperate and thus choose to 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 would equal:

$$\Pi_i^c = p_i \left[ x_{i0} - \mathcal{S}_i + \sum_{t=1}^{\infty} \delta^t (x_i^* - \mathcal{S}_i) \right]. \quad (10)$$

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

Let us now turn to the characterization of the optimal defection strategies pursued by concessionaires. Because this could happen during any tenure block, we consider the case where defection occurs during an arbitrary tenure block,  $k$ . If agent  $i$  defects during tenure block  $k$ , given all concessionaires, except  $i$ , follow simple cooperative strategies (that is, they are unconditional cooperators), the optimal defection strategy of concessionaire  $i$  is characterized as follows:

**Proposition 1.** *The optimal defection strategy of concessionaire  $i$  in tenure block  $k$  is given by:*

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

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

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

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<sup>10</sup>This turns out to be irrelevant because, as we later show, if everyone defects, the natural resource is driven extinct.

Proposition 1 states that a concessionaire who decides she will defect *sometime* during tenure block  $k$ , will decide to: (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.<sup>11</sup> Note that the optimal defection strategy does not depend on the tenure block,  $k$ .<sup>12</sup> The finding that the defection strategy is independent of the tenure block greatly simplifies the characterization of equilibrium strategies, and the corresponding present value payoff under defection is given by:

$$\Pi_i^d = p_i \left[ x_{i0} - \mathcal{S}_i + \sum_{t=1}^{(k-1)T-1} \delta^t (x_i^* - \mathcal{S}_i) + \delta^{(k-1)T} (x_i^* - \bar{e}_i) + \sum_{t=(k-1)T+1}^{kT-2} \delta^t (\bar{x}_i - \bar{e}_i) + \delta^{kT-1} \bar{x}_i \right]. \quad (11)$$

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

The payoff when patch owner  $i$  defects during tenure block  $k$  is given by (1) profit obtained while abiding by the target stock prior to the  $k^{\text{th}}$  tenure block, and (2) profit from non-cooperative harvesting during tenure block  $k$ , until finally extracting all the stock in the final period of the  $k^{\text{th}}$  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 ( $\mathcal{S}_1, \dots, \mathcal{S}_N$ ) by the regulator who wishes to replicate the socially optimal level of extraction in every patch at every time. Second, we derive necessary and sufficient conditions for cooperation to be sustained, as a function 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

Can the Limited Tenure Spatial Concessions Instrument *ever* lead to cooperation? Clearly, if the announced target stocks are sufficiently low (e.g. if  $\mathcal{S}_i = 0 \forall i$ ),

<sup>11</sup>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.

<sup>12</sup>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  $t$ .

then "cooperation" is easily achieved.<sup>13</sup> But this is of little use because low target stocks result in low resource stocks and commensurately low social welfare. Our interest is in designing the instrument to replicate the socially-optimal harvest in each patch at every time. Given the goal of achieving the socially optimal spatial extraction, 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 5.*

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 conditions under which cooperation may emerge, we proceed by assuming that concessionaires follow simple strategies: They adopt unconditional cooperative strategies which are characterized by Proposition 2. This allows us to assume compliance by  $N - 1$  concessionaires and to explore the incentives of an arbitrary concessionaire  $i$  to cooperate or defect. Specifically, this allows us to assess the potential of the instrument to induce efficient resource management. Indeed, this situation (where  $N - 1$  concessionaires adopt strategies such that they fully commit to the scheme) corresponds to the case where the last agent might have the largest incentives to defect.<sup>14</sup> 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. Under the assumption of unconditional cooperation,

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<sup>13</sup>Recall, a concessionaire is said to "cooperate" if her residual stock is at least as large as the announced target.

<sup>14</sup>We will consider the case where agents might follow punishment strategies in Section 4.1.

she simply calculates her payoff from the optimal defection strategy (characterized by Proposition 1) and compares it to her payoff from the optimal cooperation strategy. Thus, 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 a straightforward representation, given in the following result:

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

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

Here we assume that defection entails at least some harvest (i.e. that the stock is  $\bar{x}_i = \sum_{j \neq i} D_{ji}g(e_j^*) + D_{ii}g(\bar{e}_i) \geq \bar{e}_i$ ) again in order to avoid corner solutions. Proposition 3 shows two things. First, since condition 12 depends explicitly on the tenure length  $T$  corresponding to the concession system considered, the incentives to cooperate or defect depend on this parameter as well. Second, 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. Note that this is possible, e.g. consider case when  $\delta = 1$ , so the right-hand side of condition 12 is equal to zero, and the left-hand side is equal to  $x_i^* - e_i^*$ , so as long as we have an interior solution to the optimal spatial problem, then this holds. This case is 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 agents.

We have thus shown that the instrument considered can lead to efficient harvesting behavior across space and time indefinitely. 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 were potentially large, it is possible that less stringent punishments 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, Territorial Use Rights Fisheries), and financial penalties are frequently used as a complementary tool to manage local issues. In a sense, our analysis highlights that, even without accounting for this additional incentive (financial penalties), spatial limited-tenure concessions have attractive appeal. Moreover, the present instrument (and the induced punishment) has some advantages over alternative forms of punishment. For instance, the use of temporary exclusion would imply that some concessions would remain unused during a certain amount of time, which can be socially unacceptable if other people might be interested by the opportunity to enter the system.

A final remark is due. This instrument relies on monitoring and enforcement, the costs of which have not been included in the analysis. Yet real-world cases suggest that monitoring has been drastically improved with the implementation of territorial rights, and thus may be less burdensome for the resource manager. For instance, in the Punta Allen lobster fishery (Mexico), all catch of a given area must be processed through a given facility, which drastically reduces the complexity of monitoring (Sosa-Cordero et al. (2008)).

### 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. In this subsection we examine the effects of price, growth, and dispersal on the cooperation decision. Because the cooperation decision boils down to  $\Pi_i^c \geq \Pi_i^d$ , we define agent  $i$ 's *willingness-to-cooperate* by:

$$W_i \equiv \Pi_i^c - \Pi_i^d \quad (13)$$

The variable  $W_i$  has an important implication, even when cooperation is strictly ensured by the model. For example, consider two concessionaires ( $A$  and  $B$ ) who both cooperate and for whom  $W_A \gg W_B > 0$ . Then we might have the intuitive idea that concessionaire  $A$  is more likely to continue cooperating under, for example, elevated transaction costs than is concessionaire  $B$ .<sup>15</sup> We next explore how  $W_i$  depends on various parameters of the problem. Naturally, as a parameter changes, we must trace its effects through the entire system, including how it alters others' decisions. Assuming as above that the willingness to cooperate is initially positive, we summarize our findings in the following proposition:

**Proposition 4.** *Concessionaire  $i$ 's willingness-to-cooperate,  $W_i$ , is:*

- (1) *Increasing in its own economic parameter,  $p_i$ , and in growth rate and out-property of other patches,  $\alpha_j$ , and  $D_{ji}$ ,*
- (2) *Decreasing in off-property dispersal,  $D_{ij}$ .*

To help build intuition for the conclusions provided in Proposition 4,<sup>16</sup> we will call out a few special cases. First, consider the effects of an increase in productivity of connected patches ( $\alpha_j$ ). Since defection implies harvesting one's entire stock,

<sup>15</sup>Such as bargaining, negotiating, or enforcement costs not explicitly captured by our model.

<sup>16</sup>Note that the effects of other parameters ( $p_j$ ,  $\alpha_i$ , and of self-retention  $D_{ii}$ ) are difficult to sign and often ambiguous. In the Appendix we show that  $W_i$  can be increasing or decreasing in  $p_j$  and  $\alpha_i$ , while we provide cases where it is increasing in  $D_{ii}$ .

there is little opportunity (under defection) to take advantage of one's neighbor's high productivity. But under cooperation, a larger  $\alpha_j$  implies larger immigration, which translates into higher profit. A similar logic explains the result on  $D_{ji}$ . 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  $D_{ij}$ .

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  $N \times N$  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 show that a high degree of self-retention ( $D_{ii}$ ) in all patches is sufficient to ensure cooperation.

**Proposition 5.** *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.*

The basic intuition underlying Proposition 5 is that 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. That is, when spatial externalities are not too large, the concession instrument overcomes the externality caused by strategic interaction. The inverse is also intuitive: If self-retention is very low, then a large externality exists, and it may be more difficult to sustain cooperation. Naturally, formalizing this intuition 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. After accounting for all of these dynamics, we arrive at the following result:

**Proposition 6.** *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:*

$$\sum_{j \neq i} D_{ji} g(e_j^*) < \sum_{j \neq i} D_{ij} \frac{p_j}{p_i} g'(e_i^*) e_i^*. \quad (14)$$

Proposition 6 establishes that if any patch has sufficiently low self-retention, then cooperation might be destroyed. This result relies on an additional condition on the interplay between spatial characteristics and economic returns. Condition (14) may be interpreted (for a given patch) as a comparison between the present value resulting from the incoming resource and the present value of the outgoing resource. On one hand, the externality has a positive impact because the owner in the patch earns extra profit since he obtains a share of stocks from other patches; on the other hand, this owner “loses” a share of potential profits resulting from the dispersal of part of the resource (assessed at the market value where this part of the resource will be harvested).

### 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. We have derived sufficient conditions for full cooperation and for defection, and have assumed an exogenously given (arbitrary) tenure period. But, in reality, the time horizon is a policy choice that interacts with other model parameters to affect the cooperation decision. Recall that the regulator assigns to concessionaire  $i$  a target stock ( $\mathcal{S}_i = e_i^*$  by Proposition 1) and a tenure duration ( $\mathcal{T}_i = T$ ). 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 7.** *For sufficiently long tenure duration,  $T$ , cooperation cannot be sustained as an equilibrium outcome.*

Proposition 7 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, at least using the instrument analyzed here. But upon deeper inspection this result accords with economic principles. Consider

the case of very long tenure duration - in the extreme, when tenure is infinite, 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.<sup>17</sup> This result obtains precisely because the spatial externality of resource dispersal drives a wedge between the privately optimal decision and the socially optimal one.

Proposition 7 makes it clear that *long* tenure durations can never reproduce the socially optimal spatial and temporal pattern of harvest in a spatially-connected renewable resource. On the other hand, 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 than the current tenure block. In fact, it can be shown that there exists a threshold tenure length for which cooperation is sustained if and only if  $T$  is smaller than the threshold value, which we summarize as follows

**Proposition 8.** *Assume the following holds for concessionaire  $i$ :*

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

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

The condition in Proposition 8 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. Proposition 8 reveals that some longer tenure durations will also sustain cooperation, but if tenure is too long (i.e. if  $T > \bar{T}$ ), defection will surely arise. Still, in practice, very short tenure durations might entail high monitoring costs, which supports the use of longer tenures. We will further emphasize in Section 4.1 that a longer tenure duration has some advantages (in terms of the overall robustness of the instrument).

It turns out that the threshold tenure length ( $\bar{T}$ ) depends on patch level characteristics, so we define by  $\bar{T}_i$  the threshold value for concessionaire  $i$ : if  $T_i > \bar{T}_i$ , owner  $i$  will defect and if  $T_i < \bar{T}_i$ , she will cooperate. Then, by Proposition 8, cooperation can be achieved by assigning to all  $N$  concessionaires  $T = \min_i \{\bar{T}_i\}$ . Here, we briefly examine the dependence of  $\bar{T}_i$  on patch, and system-level characteristics.

The time-threshold for concessionaire  $i$  can be written as follows:

$$\bar{T}_i = 1 + \frac{\ln\left(\frac{\delta(\bar{x}_i - x_i^*) + e_i^* - \bar{e}_i}{\delta \bar{x}_i - \bar{e}_i}\right)}{\ln(\delta)} \quad (16)$$

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<sup>17</sup>Following our approach above, we focus on the incentives of a single concessionaire, and assume that the other concessionaires are unconditional cooperators. A more sophisticated set of strategies (e.g. under trigger or other punishment strategies), might weaken Proposition 7; we return to this issue in Section 4.1.

But 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 Proposition 4 (which addresses how concessionaire  $i$ 's willingness to cooperate depends on parameters of the problem), it is intuitive to think that similar results will be obtained here. Indeed, we obtain qualitatively similar results; because of this similarity, we relegate them to the Appendix.

## 4 Robustness of the instrument

To maintain analytical tractability, and to sharpen the analysis, we have made a number of simplifying assumptions about the strategies pursued by cooperators. Here, we examine the consequences of three noteworthy assumptions. First, we explore trigger strategies as a means by which cooperators might punish defectors. Second, 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 scope of applicability of trigger strategies

In Section 3, we focused on the use of simple strategies. An alternative is to use trigger strategies under which all non-defectors agree to defect immediately upon the defection of a single concessionaire. By using trigger strategies to punish defectors, all other concessionaires will know for sure that they will not get renewed at the end of their current tenure block. Thus, trigger strategies imply a form of self-punishment, which can be seen as an additional incentive scheme.<sup>18</sup> We summarize our findings on trigger strategies as follows:

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

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

where we assume  $\bar{\bar{x}}_i = \sum_j D_{ji} g(\bar{e}_j) \geq \bar{e}_i > 0$ .

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

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<sup>18</sup>It is useful to recall that the instrument analyzed here does not require that the agents use such kind of self-punishment devices in order to induce efficient resource management.

that the incentives to defect increase with a longer time horizon.<sup>19</sup> 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.

## 4.2 The case of a finite horizon

We have assumed an infinite horizon problem, so 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 begs the question of whether the instrument developed here is still effective at inducing cooperation when the horizon is finite. Here we prove that this is the case. Suppose time ends after  $K$  tenure blocks where  $1 < K < \infty$  after which all agents' 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. We formalize the result as follows:

**Proposition 10.** *Suppose time ends after the  $K^{\text{th}}$  tenure block. Provided that the following condition holds for any  $i$ :*

$$\delta x_i^* - e_i^* > \frac{1 - \delta^{T-1}}{1 - \delta^T} \left\{ \delta \bar{x}_i - (1 - \delta^T) \bar{e}_i - \delta^{T+1} \bar{\bar{x}}_i \right\}, \quad (17)$$

*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 10 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.

## 4.3 The case of stock-dependent costs

We assume in the analysis that extraction costs are linear. We might still wonder whether the instrument is robust to the case of stock-dependent marginal costs. In such a case, the expression of concessionaire  $i$ 's payoffs at period  $t$  would be given by the following expression:

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<sup>19</sup>This conclusion follows if we differentiate the expression of the difference between payoffs as a function of the time horizon.

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

where  $c'_i(s) < 0$  is continuously differentiable. In this section, our aim is only to explain briefly why the logic of Proposition 3 (the main result, which provides the conditions for the emergence of complete cooperation as an equilibrium outcome) will remain valid in this case. The proof relies mainly on two arguments.<sup>20</sup> 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  $t$  is actually time and state independent. In the case of stock-dependent costs, these two features remain valid, even though the actual characterization of the optimal defection strategy differs with respect to the case of linear costs. Then the conditions ensuring the emergence of complete cooperation will in turn differ from conditions (12), but the qualitative conclusion of Proposition 3 remains valid. From a general point of view, while using stock-dependent marginal costs would complicate the proofs of our results (and their exposition as well), we think it is unlikely to overturn the main findings of this paper (for instance, the impossibility to ensure the emergence of cooperation for sufficiently long tenure lengths).

## 5 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 around the world, and second, that many of the natural resources managed with such instruments have spatial characteristics. Despite the ubiquity with which concessions are used to manage spatial resources, they 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; indeed it is often the case that this instrument can 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 many real-world institutions that use limited-term concessions to manage natural resources. Second, unlike an initial intuition, the effect of a longer

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<sup>20</sup>We provide the key arguments of the proof. The full details are available from the authors upon request.

time horizon is usually negative. This is in contradiction with the case without strategic interactions as depicted in Costello and Kaffine (2008).

Several observations bear further discussion. First, we have considered a quite secure tenure system, in the sense that renewal is ensured as long as the target is attained. This allows us to focus on the effects of the spatial characteristics of the problem. Introducing a probability of renewal (as in Costello and Kaffine (2008)) would require characterizing the threshold value over which cooperation could be induced. Second, we have not explicitly included monitoring of the stock and enforcement, which may prove to be important. It seems plausible that endogenous enforcement activity would be strengthened by parameters that induce persistent cooperation over time, particularly when monitoring involves capital expenditures. Moreover, real-world cases of concessions (such as Territorial Use Rights Fisheries) seem to 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.

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 would 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 might be considered a Stackelberg leader with incentives based on things such as a concern for option values of bioeconomics systems. The focus in this study was to analyze choices of tenure lengths that would be consistent with inducing agents to cooperate. A next step could involve introducing a variety of regulators' objectives.

Overall, these results suggest that if implemented with care, the limited-tenure spatial concession can achieve near socially-optimal outcomes and yet still allow concessionaires to make decentralized decisions over harvest all while the government retains regulatory authority to require adherence to certain restrictions. Our results also suggest that this class of 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. At final period  $kT - 1$ , concessionaire  $i$ 's problem is to maximize

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

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:

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

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:

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

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. This concludes the proof.

### 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:

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

Simplifying this inequality, we obtain:

$$\delta D_{ii} (g(e_{it}) - g(e_i^*)) > e_{it} - e_i^*. \quad (18)$$

Since  $g(\cdot)$  is continuously differentiable and increasing, we know there exists  $e_i \in ]e_i^*, e_{it}[$  such that  $g(e_{it}) - g(e_i^*) = (e_{it} - e_i^*) g'(e_i)$  and we can rewrite expression 18 as follows:

$$\delta D_{ii}(e_{it} - e_i^*) g'(e_i) > e_{it} - e_i^*,$$

or

$$g'(e_i) > \frac{1}{\delta D_{ii}} = g'(\bar{e}_i).$$

We thus deduce that (since  $g(\cdot)$  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 simple strategies) then this concessionaire's payoff is  $\Pi_i^d = p_i A$ , where :

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

Now, using Condition (10), we compute  $\Pi_i^c - \Pi_i^d = p_i B$ , with:

$$B = \left[ \frac{\delta^{kT+1}}{1 - \delta} (x_i^* - e_i^*) - \delta^{kT} (e_i^* - \bar{e}_i) - \frac{\delta^{kT+1}(1 - \delta^{T-1})}{1 - \delta} (\bar{x}_i - \bar{e}_i) - \delta^{(k+1)T-1} \bar{e}_i \right] \quad (19)$$

$$= \frac{\delta^{kT} p_i}{1 - \delta} [\delta x_i^* - e_i^* - (1 - \delta^{T-1})(\delta \bar{x}_i - \bar{e}_i)]. \quad (20)$$

The conclusion follows from Equality (20).

### Proof of Proposition 5

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 (19) when  $k=0$ ) we know that:

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

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:

$$p_i \left[ \frac{\delta^T}{1 - \delta} (x_i^* - e_i^*) - \delta^{T-1} e_i^* \right] = \frac{\delta^{T-1} p_i}{1 - \delta} (\delta x_i^* - e_i^*). \quad (21)$$

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 (21) as follows:

$$\frac{\delta^T}{1-\delta}(\delta x_i^* - e_i^*) = \frac{\delta^T}{1-\delta}[\delta g(e_i^*) - \delta g'(e_i^*)e_i^*] = \frac{\delta^{T+1}}{1-\delta}[g(e_i^*) - g'(e_i^*)e_i^*]. \quad (22)$$

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:

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

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 6

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

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

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.<sup>21</sup> 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 14 holds), then  $\delta x_i^* - e_i^*$  is negative, which concludes the proof.

<sup>21</sup>Indeed,  $\delta \bar{x}_i - \bar{e}_i = \delta \sum_{j \neq i} D_{ji} g(e_j^*) + \delta D_{ii} g(\bar{e}_i) - \delta D_{ii} g'(\bar{e}_i) \bar{e}_i = \delta \sum_{j \neq i} D_{ji} g(e_j^*) + \delta D_{ii} (g(\bar{e}_i) - g'(\bar{e}_i) \bar{e}_i) > 0$  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.

## Proof of Proposition 7

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

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 (19) 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

$$p_i \left[ \bar{e}_i - e_i^* + \frac{\delta}{1-\delta}(x_i^* - e_i^* - \bar{x}_i + \bar{e}_i) \right]. \quad (23)$$

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 (23):

$$\frac{p_i}{1-\delta}[\delta D_{ii}(g(e_i^*) - g(\bar{e}_i)) - (e_i^* - \bar{e}_i)] < \frac{p_i}{1-\delta}[\delta D_{ii}g'(\bar{e}_i) - 1](e_i^* - \bar{e}_i). \quad (24)$$

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 (23) 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 8

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 6). 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  $\bar{T}_i > 1$ .<sup>22</sup> Then, again using the proof of Proposition 5 enables us to conclude that concessionaire  $i$  will have incentives to defect as soon as the renewal time horizon is larger than  $\bar{T}_i$ .

For  $T = 2$  the value of the function is given by the following expression:

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

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 9

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

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

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

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

The conclusion follows from this equality.

## Proof of Proposition 10

First, consider what happens during the final tenure block  $K$ . Using backward induction reveals that any agent  $i$ 's strategy during that block is characterized by  $e_{i,KT-1} = 0$ , and for any other period  $(K-1)T \leq t \leq KT-2$  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 agent  $i$  will defect. But in order to reach the final tenure block all agents will have managed the resource cooperatively (for the first  $K-1$  tenure blocks). Thus, cooperative agents will play as follows (the first period of the first tenure block being  $t=0$ ):

<sup>22</sup>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.

- during the first  $K - 1$  tenure blocks (thus from  $t = 0$  to  $t = (K - 1)T - 1$ ) agent  $i$  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  $t = (K - 1)T$ , agent  $i$  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, agent  $i$  chooses  $e_i = \bar{e}_i$  and the stock level is  $\bar{x}_i = \sum_j D_{ji} g(\bar{e}_j)$ ;
- Finally, at  $t = KT - 1$  we have  $e_i = 0$  and  $x_i = \bar{x}_i$ .

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

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

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

- From  $t = 0$  to  $t = (k - 1)T - 1$  agent  $i$  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  $t = (k - 1)T$ , agent 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, agent  $i$  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  $\Pi_i^c$  and  $\Pi_i^d$ , we obtain:

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

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

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

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

$$\Phi'(k) = \delta^{(K-k)T} T \ln(\delta) \{ \delta x_i^* - e_i^* - (1 - \delta^{T-1}) [\delta \bar{x}_i - \bar{e}_i] \}. \quad (25)$$

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

$$\delta x_i^* - e_i^* > (1 - \delta^{T-1}) (\delta \bar{x}_i - \bar{e}_i), \quad (26)$$

Then we have

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

This implies that the term between brackets on the right hand side of Equality (25) 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:

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

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

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

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

Finally, we can show that Condition 17 is more stringent than the condition ensuring cooperation under the infinite horizon instrument (Condition 26). Indeed, we have:

$$\begin{aligned} \frac{1 - \delta^{T-1}}{1 - \delta^T} \{ \delta \bar{x}_i - (1 - \delta^T) \bar{e}_i - \delta^{T+1} \bar{x}_i \} - (1 - \delta^{T-1}) [\delta \bar{x}_i - \bar{e}_i] &= \\ &= \frac{1 - \delta^{T-1}}{1 - \delta^T} \delta^{T+1} [\bar{x}_i - \bar{x}_i] > 0. \end{aligned}$$

This inequality implies that, as soon as Condition 17 is satisfied then Condition 26 is satisfied:

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

but the opposite does not always hold true. In particular, 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 of the instrument (the instrument is robust in this sense).

## Supplementary Material: proof of Proposition 4 and comparative statics on the time horizon (given by (16))

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

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

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:

$$\frac{d\bar{x}_i}{d\theta_i} = \frac{\partial \bar{x}_i}{\partial \bar{e}_i} \cdot \frac{\partial \bar{e}_i}{\partial \theta_i} + \frac{\partial \bar{x}_i}{\partial \theta_i} + \sum_{j \neq i} \frac{\partial \bar{x}_i}{\partial e_j^*} \cdot \frac{\partial e_j^*}{\partial \theta_i} \quad (27)$$

$$\frac{d\bar{x}_i}{d\theta_j} = \frac{\partial \bar{x}_i}{\partial \theta_j} + \sum_{l \neq i} \frac{\partial \bar{x}_i}{\partial e_l^*} \cdot \frac{\partial e_l^*}{\partial \theta_j} \quad (28)$$

$$\frac{dx_i^*}{d\theta_i} = \frac{\partial x_i^*}{\partial \theta_i} + \sum_j \frac{\partial x_i^*}{\partial e_j^*} \cdot \frac{\partial e_j^*}{\partial \theta_i} \quad (29)$$

$$\frac{dx_i^*}{d\theta_j} = \frac{\partial x_i^*}{\partial \theta_j} + \sum_l \frac{\partial x_i^*}{\partial e_l^*} \cdot \frac{\partial e_l^*}{\partial \theta_j} \quad (30)$$

and the residual stock levels

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

## A. Impact on the emergence of cooperation

Using Expressions (27) to (30) 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 agent  $i$ 's willingness to cooperate by using Expressions (27) to (30) and the table in order to compute the following expression:

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

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

Table 1: Computations of derivatives

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

$$\frac{\partial e_i^*}{\partial p_i} \left( \delta \frac{\partial x_i^*}{\partial e_i^*} - 1 \right) + \sum_{j \neq i} \frac{\partial e_j^*}{\partial p_i} \left[ \delta \frac{\partial x_i^*}{\partial e_j^*} - \delta(1 - \delta^{T-1}) \frac{\partial \bar{x}_i}{\partial e_j^*} \right] \quad (31)$$

$$\Leftrightarrow \frac{\partial e_i^*}{\partial p_i} (\delta D_{ii} g_{e_i^*} - 1) + \sum_{j \neq i} \frac{\partial e_j^*}{\partial p_i} [\delta D_{ji} g_{e_j^*} - \delta(1 - \delta^{T-1}) D_{ji} g_{e_j^*}] \quad (32)$$

$$\Leftrightarrow -\frac{\partial e_i^*}{\partial p_i} (1 - \delta D_{ii} g_{e_i^*}) + \sum_{j \neq i} \frac{\partial e_j^*}{\partial p_i} \delta^T D_{ji} g_{e_j^*} > 0 \quad (33)$$

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  $\frac{d(\Pi_i^c - \Pi_i^d)}{dp_i} > 0$  if the condition regarding agent  $i$ 's *willingness-to-cooperate* is satisfied. This means that an increase in  $p_i$  results in an increase in the value of  $\frac{d(\Pi_i^c - \Pi_i^d)}{dp_i}$ , thus an increase in the *willingness-to-cooperate*.

### Effect of $p_j$ , $j \neq i$

In this case we have

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

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  $\frac{d(\Pi_i^c - \Pi_i^d)}{dp_j}$  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  $\frac{d(\Pi_i^c - \Pi_i^d)}{dp_j}$ ) 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  $\frac{d(\Pi_i^c - \Pi_i^d)}{dp_j}$  is negative.

## Impact of growth, $\alpha$

### Effect of $\alpha_i$

We analyze the effect of  $\alpha_i$  on agent  $i$ 's willingness to cooperate. We have:

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

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

If  $D_{ii} = 1$ , then  $1 - \delta D_{ii} g_{e_i^*} = 0$  and  $\frac{d(\Pi_i^c - \Pi_i^d)}{d\alpha_i} > 0$  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 $\alpha_j$ , $j \neq i$

We analyze the effect of  $\alpha_j$  on agent  $i$ 's willingness to cooperate. We have:

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

An increase in  $\alpha_j$  increases the willingness-to-cooperate of agent  $i$ .

## Impact of dispersal rate, $D$

### Effect of $D_{ii}$

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

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

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  $\frac{d(\Pi_i^c - \Pi_i^d)}{dD_{ii}}$  to be positive).

### Effect of $D_{ij}$

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

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

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

### Effect of $D_{ji}$

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

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

An increase in dispersal from patch  $j$  to patch  $i$  increases agent  $i$ 's incentives to cooperate.

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

Differentiating Condition (16) with respect to parameter  $\theta$ , we have:

$$\frac{d\bar{T}_i}{d\theta} = \frac{\partial \bar{T}_i}{\partial \theta} + \frac{\partial \bar{T}_i}{\partial \bar{x}_i} \frac{d\bar{x}_i}{d\theta} + \frac{\partial \bar{T}_i}{\partial \bar{e}_i} \frac{d\bar{e}_i}{d\theta} + \frac{\partial \bar{T}_i}{\partial x_i^*} \frac{dx_i^*}{d\theta} + \frac{\partial \bar{T}_i}{\partial e_i^*} \frac{de_i^*}{d\theta} \quad (34)$$

$$= \frac{1}{\ln(\delta) [\delta(\bar{x}_i - x_i^*) + e_i^* - \bar{e}_i]} \left[ \frac{\partial e_i^*}{\partial \theta} - \delta \frac{dx_i^*}{d\theta} + \left( \frac{\delta x_i^* - e_i^*}{\delta \bar{x}_i - \bar{e}_i} \right) \left( \delta \frac{d\bar{x}_i}{d\theta} - \frac{d\bar{e}_i}{d\theta} \right) \right] \quad (35)$$

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 (35) is always negative. Thus, in order to sign the effect of parameter  $\theta$  on  $\bar{T}_i$  we examine the term between brackets. Using expressions (27)-(30) and Table 1, we check that  $\delta \frac{d\bar{x}_i}{d\theta} - \frac{d\bar{e}_i}{d\theta} \geq 0$ . 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 (35).

### Effect of $p_j$ , $j \neq i$

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

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

$$\Leftrightarrow \frac{\partial e_i^*}{\partial p_j} (1 - \delta D_{ii} g_{e_i^*}) + \delta \left( \frac{\delta(x_i^* - \bar{x}_i) - e_i^* + \bar{e}_i}{\delta \bar{x}_i - \bar{e}_i} \right) \left( D_{ji} g_{e_j^*} \frac{\partial e_j^*}{\partial p_j} + \sum_{l \neq i, j} D_{li} g_{e_l^*} \frac{\partial e_l^*}{\partial p_j} \right) \quad (38)$$

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. Specifically, we have:

- 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 $\alpha_i$

$$\frac{\partial e_i^*}{\partial \alpha_i} \left( 1 - \delta \frac{\partial x_i^*}{\partial e_i^*} \right) - \delta \frac{\partial x_i^*}{\partial \alpha_i} + \left( \frac{\delta x_i^* - e_i^*}{\delta \bar{x}_i - \bar{e}_i} \right) \left[ \delta \left( \frac{\partial \bar{x}_i}{\partial \alpha_i} + \frac{\partial \bar{x}_i}{\partial \bar{e}_i} \frac{\partial \bar{e}_i}{\partial \alpha_i} \right) - \frac{\partial \bar{e}_i}{\partial \alpha_i} \right] \quad (39)$$

$$\Leftrightarrow \frac{\partial e_i^*}{\partial \alpha_i} (1 - \delta D_{ii} g_{e_i^*}) - \delta D_{ii} \left[ g_{\alpha_i^*} - g_{\bar{\alpha}_i} \left( \frac{\delta x_i^* - e_i^*}{\delta \bar{x}_i - \bar{e}_i} \right) \right] \quad (40)$$

We obtain the following conclusion: If  $\delta D_{ii}$  is sufficiently small while  $\bar{e}_i$  remains positive, then the sign of expression (37) is positive, which implies that  $\bar{T}_i$  would decrease when the growth-related parameter increases in patch  $i$ .

### Effect of $D_{ii}$

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

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

## Documents de Recherche parus en 2016

DR n°2016 - 01: Nicolas QUEROU, Agnes TOMINI et Christopher COSTELLO  
« Spatial concessions with limited tenure»

**Contact :**

Stéphane MUSSARD : [mussard@lameta.univ-montp1.fr](mailto:mussard@lameta.univ-montp1.fr)

