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ABSTRACT

We analyze theoretically an institution called a "limited-tenure concession" for its ability to induce efficient public goods contribution and common-pool resource extraction. The basic idea is that by limiting the tenure over which an agent can enjoy the public good, but offering the possibility of renewal contingent on ample private provision of that good, efficient provision may be induced. We first show in a simple repeated game setting that limited-tenure concessions can incentivize socially-efficient provision of public goods. We then analyze the ability of this instrument to incentivize the first best provision for common-pool natural resources such as fish and water, thus accounting for spatial connectivity and natural growth dynamics of the resource. The duration of tenure and the dispersal of the resource play pivotal roles in whether this limited-duration concession induces the socially optimal private provision. Finally, in a setting with costly monitoring, we discuss the features of a concession contract that ensure first-best behavior, but at least cost to the implementing agency.

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1 Introduction

The impediments to private provision of public goods, carefully described over half a century ago (Samuelson 1954; Buchanan 1965), remain pervasive and economically relevant today (Kotchen 2006; Marx and Matthews 2000; Cornes and Sandler 1996). While governments can (and do) provide these goods, there is a perpetual quest to develop institutions and incentives that give rise to efficient private provision. In this paper we formalize and analyze an institution called a “limited-tenure concession” for its ability to induce the efficient private provision of public goods.

While we will analyze a general model of public goods, we are motivated by the tragedy of the commons, a particular public goods setting in which natural resources are over-extracted by agents who fail to internalize the consequences of their extraction on others' payoffs. In this way, agents' over-extraction can be viewed as under-provision of the public good. Even today many natural resources including forests, fisheries, and irrigation water are over-extracted and are thus inefficiently provided.[1] One increasingly common approach is to devolve ownership of these resources to individuals, communities or cooperatives; the idea being that this assignment of property rights creates a sole-owner-like incentive to steward the resource. But even in that setting, because these resources often move in space, one owners' extraction affects other owners' future payoffs, and the externality persists. In other words, even perfectly delineated spatial property rights cannot solve the tragedy of the commons for spatially-connected natural resources.

We find that over-extraction of natural resources in a common pool is a particular public goods setting that is ripe for limited-tenure concessions. Here, a concession is a limited-duration assignment of property rights, under which the temporary owner is completely autonomous and can behave in any manner she sees fit - that is, she is free to extract as much or as little as she wishes over the duration of her tenure.[2] Two parameters of a concession contract will turn out to be pivotal for our analysis. First, the *duration* of tenure plays an important role in incentives and can make, or break, the ability of the concession to induce efficient provision of the public good. Second, we allow for the possibility of *renewal* of the concession contract, provided that certain conditions have been met. We will show that the enticement of renewal

[1]Other relevant examples include green goods and climate protection infrastructure, provided their collective benefits may be potentially excludable. We refer to Section 2 for a discussion of other consistent real-world examples.

[2]In real world settings, trade in concession contracts is usually forbidden because the resource is held in public trust and approved concessionaries must meet certain criteria. However, allowing trade in concession contracts is innocuous in our model so long as the buyer is bound by the same terms as was the seller.

can induce efficient private provision of a public good, even from completely self-interested parties.

Limited-tenure concessions are also applicable across a much broader set of public goods, whose efficient provision is hindered by free-riding incentives.[3] In the general public goods setting, a concession can be thought of as a limited-duration assignment of a property right to a temporary owner. Over her tenure she enjoys all the benefits of the public good and she may also decide to contribute to the public good. At the conclusion of her tenure there is the possibility of renewal, which is contingent on her private contributions over the preceding tenure block. If her tenure is not renewed, then she is excluded from enjoying the future benefits of the public good. It is intuitive to see how the ability to exclude the player from enjoying the future benefits of the public good could induce private provision in the present. We begin the analysis with a simple, stylized repeated public goods contribution game. That simple analysis highlights the important tradeoffs and incentives engendered by a limited-tenure concession.

After illustrating the principal incentives of this intervention in a highly stylized setting, we turn to a more substantial application to common pool natural resources. Natural resources generalize the simple case in important dimensions including natural resource growth (i.e. a production function in which next year's resource stock depends on this year's resource stock), mobility (water flows and fish swim), and heterogeneity (e.g. growth or movement can differ over space) in incentives across users. These features may exacerbate the tragedy of the commons[4] and we examine whether, and how, these features undermine the ability of limited-tenure concessions to induce efficient private provision. When concessions are awarded over a fixed geographical area, the resources they are meant to encapsulate may disperse beyond the concessionaire's domain; this could significantly alter incentives for efficient resource use, since this implies a spatial externality.[5] We thus amend the model to account for these characteristics. Introducing a set of spatially-distinct property right owners, we consider three management regimes: (i) the socially optimal regime, (ii) the decentralized regime and (iii) the concession regime. The last regime involves assigning limited-duration tenure of each patch to a concessionaire, with conditional renewal. The grantor of the concession (which we call a "regulator") announces for each patch

[3]Bergstrom et al. (1986) provides the seminal paper on this issue, which has received attention in many areas, including the environmental field (Vicary 2000; Kotchen 2006; Kotchen 2009).

[4]For instance, Cornes and Sandler (1983) provide a detailed analysis of this tragedy.

[5]The world's oceans consist of about 200 property right assignments (exclusive economic zones) traversed by species such as tuna, sharks, and whales (White and Costello 2014). The mismatch between the scales of property rights and of the resource is emphasized as a limitation (Aburto-Oropeza et al. 2017) for mobile resources (Costello et al. (2015) or Kapaun and Quaas (2013)).

a minimum stock below which the concessionaire should never extract. This is a stylized version of how many concessions are implemented.[6] Each concessionaire must decide whether to comply or to defect, given that her payoff will depend on others' strategies. Complying guarantees renewal, which raises future payoffs, while driving the stock below the requirement returns large current payoffs, but ensures the contract will not be renewed. One special case of this model is when all agents have perpetual decentralized property rights, and we show that limited-tenure concessions outperform this oft-touted benchmark.

We show that limited-tenure concessions can induce the first best (that is, socially optimal) behavior in this setting, and analyze the properties ensuring cooperation. We find an interesting result: longer tenure is more likely to lead to defection from the first best. This result has crucial implications for policy design, and it seems to contradict the intuition that more secure property rights (here, the longer the tenure duration) give rise to more efficient resource use. Indeed, Costello and Kaffine (2008) show that any tenure length may induce efficient resource use, provided the renewal probability is high enough. In our paper, under a long tenure period the regulator loses the ability to affect an agent's incentives via the promise of tenure renewal. Thus, for sufficiently long tenure length, concessionaires always defect: tenure must not be too long. Finally, we discuss how concessions may still induce first-best behavior even when monitoring and enforcement are imperfect and costly.

This discussion highlights the shortcomings of short tenure equal to, say, a single period. That case corresponds more closely to command and control regulation. Here, however, compliance is incentivized by the promise of renewal, rather than punished with a monetary penalty. Short tenure can induce efficient behavior, but would be costly to implement if more frequent monitoring brings higher costs. Thus, shorter tenure may induce stronger incentives to comply, but could increase the expected monitoring costs. We analytically solve for the tenure length ensuring compliance at least cost.

Overall this paper makes three primary contributions. First, we show in a re-

[6] TURF systems in Japan, Mexico and Chile contain maximum harvest provisions, whose adherence is required for renewal. As a yearly stock assessment is carried out by consultants approved by the government to determine a total allowable catch (TAC) for each TURF, such a requirement may translate into a minimum stock requirement (Hilborn et al. (2005)). Wildlife management areas in developing countries rely on ownership devolution to local communities and also require coordination from governments (Pailler et al. (2015)). Groundwater is increasingly managed by property rights, where an adjudication process relies on a watermaster to enforce the terms of the property right. Because groundwater migrates spatially according to geological features, the groundwater management setting shares the basic features of our concession system (see Ayres et al. (2018) for real-world cases).

peated public good contribution game that limited-tenure concessions can induce efficient provision of public goods. Second, we extend the model to account for characteristics of common-pool resources more typical in natural resource settings: spatially-connected resources, and growth dynamics. We show that the system can incentivize the first best. Finally, in a setting with costly monitoring of a concession contract by an implementing agency, we discuss the features that ensure first-best behavior, but at least cost to implement. All results are analytically derived, allowing us to draw general conclusions.

The paper is structured as follows: Section 2 introduces a motivating model of the private contribution to a public good and highlights how a concession alters incentives for private provision. In Section 3 the model is generalized to allow for heterogeneity and complex resource dynamics. In Section 4 we highlight the conditions for cooperation with an emphasis on spatial characteristics of the model and the tenure length. Various extensions are discussed in Section 5. A comparison with other potential policies is provided in Section 6 and Section 7 concludes the paper. Proofs are provided in an Appendix.

2 A simple model of public good contributions

To motivate our main contribution, and to build intuition, we begin with a simple model of individual behavior with both private and public consequences. Consider initially a static game in which (exogenous) N agents interact, where each agent takes other agents' actions as given. Agent i chooses action (or "contribution") z_i, which confers a public benefit but comes at a private cost. Her utility in this static game is given by:

$$W\left(\sum_l z_l\right) + u_i(\Phi - z_i) \tag{1}$$

Here, the function $W(\cdot)$ represents the public component of utility and $u_i(\cdot)$ represents the private component. The fixed parameter Φ denotes an agent's endowment (or maximum effort level). Assuming that both functions are increasing and concave ensures an interior equilibrium.[7] This is a version of the canonical public goods model popularized by Samuelson (1954). We slightly depart from this canonical model by assuming that the public and private components of utility are bundled.[8]

[7] Existence and uniqueness further require that $W'((N-1)\Phi) \geq u_i'(\Phi)$ and $W'(\Phi) \leq u_i'(0)$ hold for any agent i.

[8] This public good is more aptly referred to as an *excludable public good*, because we restrict its

Here, increasing contribution z_i comes at the cost of decreasing the private benefits $u_i(\Phi - z_i)$. It is straightforward to show that agent i under-provides this excludable public good because she fails to consider the beneficial effect of a larger contribution on other players' utilities. That is, agent i maximizes Equation 1 by setting $u_i'(\Phi - \hat{z}_i) = W'(\sum_l \hat{z}_l)$, while the social planner would like to maximize the sum of utility across all agents, so she sets $u_i'(\Phi - z_i^*) = NW'(\sum_l z_l^*)$. Straightforward comparative statics reveals that private agents will contribute too little: $\hat{z}_i < z_i^*$.

Attempting to incentivize efficient provision, consider a new institution under which this game is repeated every period for a limited duration tenure. That is, each period, all N members contribute to, and enjoy the benefits from, public good provision, but any player i's tenure lasts only for a limited duration. For example, tenure may extend for a period of $T = 10$ years. A manager has the ability to renew tenure to agent i, and agrees to do so if and only if agent i has acted responsibly, for example if and only if she has chosen z_i^* in every preceding period (up to T). This limited-duration tenure with the possibility of renewal is the focus of the rest of this paper, and in this section we use this simple setup to illustrate how this institution can induce efficient provision of the public good.

Clearly, the enticement of renewal induces a tension in agent i's decision about her contribution. On one hand, if she chooses to defect from the renewal rule stated by the manager (while all other agents choose to comply and thus collectively contribute $\sum_{l \neq i} z_l^*$), she maximizes her payoff in any given period by choosing a contribution to the public good that is lower than the socially optimal level (z_i^D instead of z_i^*, where defection strategy z_i^D is, implicitly, $u_i'(\Phi - z_i^D) = W'\left(\sum_{l \neq i} z_l^* + z_i^D\right)$.). She is permitted do so each period for the duration of her tenure (which lasts T periods). On the other hand, the revocation rule ensures that by doing so, she will obtain zero benefit after T periods. Instead, by contributing z_i^* in all T periods, she is ensured renewal for another tenure block. This tradeoff - of large current period benefits from defection vs. infinite, though lower, benefits from cooperation - is similar to the tradeoff in a Nash Reversion punishment strategy (see, e.g., Mas-Colell et al. (1995)), except that: (1) the punishment happens at date T (not immediately upon defection), (2) the punishment payoff is zero (rather than the Nash equilibrium payoff), and (3) under this setup, other players besides i are not required to play Nash upon defection. Here, it is the limited-tenure institution that is designed to induce efficient contributions and punishment comes in the form of the failure to renew tenure. We refer to this institution as a "limited-tenure concession".

We now sketch why this type of concession contract can be designed to maintain

consumption to a limited set of N agents. In this way our model departs from a pure public good setting, see Wang and Zudenkova (2016) for a recent analysis.

cooperation around z_i^*, and that there is a Folk-theorem-like result that ensures cooperation (Mailath and Samuelson (2006), and see Dutta (1995) for a generalization to stochastic games). If other agents comply, how will i respond? In that case, agent i's infinite horizon cooperation payoff is given by:

$$\Pi_i^C = \frac{u_i(\Phi - z_i^*) + W\left(\sum_l z_l^*\right)}{1-\delta} \tag{2}$$

where δ is the discount factor. Instead, if agent i defects, it can be shown that she will do so in the first tenure block, so her defection payoff is:

$$\Pi^D = \frac{\left(1-\delta^{T+1}\right)}{1-\delta}\left[u_i(\Phi - z_i^D) + W\left(\sum_{l\neq i} z_l^* + z_i^D\right)\right] + 0 \tag{3}$$

which is just the defection payoff for a total of T periods and zero thereafter.[9] In this simple situation the agent compares $\Pi_i^C \lesseqgtr \Pi_i^D$. Straightforward algebraic manipulation implies that a necessary and sufficient condition ensuring that the limited-tenure instrument induces the first-best outcome as an equilibrium is the following:

$$\delta^{T+1} > \frac{u_i(\Phi - z_i^D) + W(\sum_{l\neq i} z_l^* + z_i^D) - (u_i(\Phi - z_i^*) + W\left(\sum_l z_l^*\right))}{u_i(\Phi - z_i^D) + W(\sum_{l\neq i} z_l^* + z_i^D)} \tag{4}$$

The right hand side is the percentage loss in single-period utility to agent i from cooperating, rather than defecting. If the discount factor is sufficiently large, so agents are sufficiently patient, then cooperation will always be supported as an equilibrium outcome. Notice that, depending on the fundamentals, the actual value of the bound defined in condition 4 might not be very high. One interesting consequence of Condition 4 is that longer tenure blocks (i.e. larger T) require higher discount factors (i.e. lower discount rates) to sustain cooperation - sustaining cooperation under a long tenure period requires more patience on the part of the agents.

Even the simple repeated game presented here provides some useful and interesting insights about the ability of a limited-tenure concession to induce socially optimal provision of a public good. Versions of limited-tenure concessions are employed commonly in real-world settings in which club members are expected to regularly contribute to an excludable public good. For example, the North Atlantic Treaty Organization was one of the first such clubs to receive focused attention by economists (Olson and Zeckhauser 1966). There, 29 member countries each contributes financially and agrees to uphold certain democratic and humanitarian ideals. In exchange

[9]The defection payoff is zero thereafter because the public and private components of utility are bundled.

for the contributions, members receive public good defense (among other) benefits that depend on others' contributions. If a member refuses to contribute the agreed-upon share (which, by the way, differs among members), they face likely expulsion from the club (and thus exclusion from the future benefits), though this process can take time (so $T > 1$). Most social clubs, such as the historical Confrerie des Chevaliers du Tastevin in Burgundy, France (12,000 members), the exclusive Yellowstone Club in Montana (250 members), and the service-oriented Rotary Club International (1.2 million members) require contributions of time, money, and expertise to sustain membership and enjoy club benefits. Formal charters ensure that the failure to contribute leads to exclusion from the club's future benefits. In natural resources, some clubs come in the form of international environmental agreements. For example, to govern fisheries on the high seas, regional fishery management organizations function as clubs where member countries contribute resources and data to the group, and agree to uphold certain sustainable practices. Failure to meet those requirements leads to future exclusion of public goods such as scientific information and management coordination. Thus, the limited-tenure concession concept may even be applicable to international settings, provided there is a mechanism to exclude defecting members from public goods.

This paper is motivated by a class of public goods challenges that has historically led to the tragedy of the commons. We are interested in whether a limited-tenure concession can help reverse over-extraction incentives for complex, spatially-connected natural resources, so the simple model presented above will require some elaboration. In what follows, we maintain the basic idea behind this simple model, but allow for a sophisticated array of economic and ecological interactions including spatially owned natural resource patches, natural resource growth and dispersal across space: we thus move from a repeated game to a spatially dynamic game setting. Modeling this richer environment allows us to draw conclusions about the features of a natural resource setting in which limited-tenure concessions can be designed to achieve socially efficient outcomes.

3 Model & strategies

We now introduce a model of natural resource exploitation with spatially-connected property owners. We then home-in on the incentives for harvest strategies corresponding to three property right regimes: a social planner optimizing resource extraction over space and time; decentralized perpetual property right holders; the case of decentralized limited-tenure concessions, on which we focus. The social planner's benchmark and the case of perpetual property right holders have been analyzed previously in the literature: we briefly state the corresponding properties.

3.1 The model

We follow the basic setup of Costello et al. (2015) where a natural resource stock is distributed heterogeneously across a discrete spatial domain consisting of N patches or properties. Patches may be heterogeneous in size, shape, economic, and environmental characteristics, and resource extraction can occur in each patch. Using a discrete-time model, the stock residing in property i at the beginning of time period t is given by x_{it}, and harvests undertaken in that property, h_{it}, reduces the stock over the course of that time period: Thus leaves a "residual stock" at the end of the period of $e_{it} \equiv x_{it} - h_{it}$. The residual stock may grow, and the growth conditions may be patch-specific denoted by the parameter α_i. Finally, as the resource is mobile and can migrate around this system, we follow the natural science literature (see, e.g., Nathan et al. (2002), or Siegel et al. (2003)) who denote dispersion by $D_{ij} \geq 0$ the fraction of the resource stock in patch i that migrates to patch j in a single time period.[10] Since some fraction of the resource may indeed flow out of the system entirely, the dispersal fractions need not sum to one: $\sum_i D_{ji} \leq 1$. The equation of motion in patch i is thus given as follows:

$$x_{it+1} = \sum_{j=1}^{N} D_{ji} g(e_{jt}, \alpha_j). \tag{5}$$

Here $g(e_{jt}, \alpha_j)$ is the period-t resource growth in patch j. As usual we require that $\frac{\partial g(e,\alpha)}{\partial e} > 0$, $\frac{\partial g(e,\alpha)}{\partial \alpha} > 0$, $\frac{\partial^2 g(e,\alpha)}{\partial e^2} < 0$, and $\frac{\partial^2 g(e,\alpha)}{\partial e \partial \alpha} > 0$.[11] We also assume that extinction is absorbing, $g(0; \alpha_j) = 0$, and that the growth rate is finite, $\frac{\partial g(e,\alpha)}{\partial e}|_{e=0} < \infty$.[12] All standard biological production functions are special cases of $g(e, \alpha)$.

We assume that both price and marginal harvest cost are constant in a patch,

[10]When $j = i$ parameter D_{ii} denotes the fraction of the resource stock in patch i that remains in this patch. This model assumes density-independent dispersal parameters, D_{ij}. We thus follow a large part of the literature on metapopulation and source-sink dynamics (Sanchirico and Wilen 2009). This allows us to analyze the comparative statics effect of dispersal on cooperation vs. defection incentives. In Section 5.4 we consider the case of density-dependent dispersal.

[11]These assumptions must be satisfied within the relevant range of variable e. The logistic growth function is consistent with them.

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

though they can differ across patches. The resulting *net price* is given by p_i.[13] The current profit from harvesting $h_{it} \equiv x_{it} - e_{it}$ in patch i at time t is:

$$\Pi_{it} = p_i \left(x_{it} - e_{it}\right). \tag{6}$$

We will employ this framework to compare the outcome and welfare implications of three alternative property right systems. At this stage it is important to make the following observation. Real world natural resource management is more complex than the setting depicted here. For instance, there could be more complicated cost structures. We propose a relatively simple, analytically tractable model to gain insights on the performance of our concession instrument, while keeping the most relevant features when studying this issue. This model allows for dynamic and spatial externalities, and for strategic behavior between patch owners: we thus consider a spatial dynamic game, instead of a repeated game as in Section 2. It allows to gain sharp insights on the effects of ecological and economic fundamentals and of features of the instrument (tenure length, target stock requirements) on its performance. We will obtain sharp analytical results by exploiting the structure of our dynamic and spatial game. We will derive closed form expressions of the owners' optimal payoffs when committing to the instrument, and when following their best defection strategies. This is necessary to analytically assess the performance of the instrument. We discuss the case of stock-dependent costs in Section 5.3.[14]

3.1.1 Social Planner's Problem

Our benchmark is the case of the social planner who maximizes the net present value of profit across the entire domain given the discount factor δ. Her objective is:

$$\max_{\{e_{1t},\ldots,e_{Nt}\}} \sum_{t=0}^{\infty} \sum_{i=1}^{N} \delta^t p_i \left(x_{it} - e_{it}\right), \tag{7}$$

subject to the equation of motion (5) for each patch $i = 1, 2, ..., N$. Focusing on interior solutions, in any patch i, the planner should achieve the residual stock level:

$$g_i'\left(e_{it}^*\right) = \frac{p_i}{\delta \sum_j D_{ij} p_j} \tag{8}$$

[13] This assumption is fairly common and consistent with cases where the market price is the same in all patches, while marginal costs are patch-specific (due to geographical locations, different costs of access). Moreover, for many natural resources the number of implemented concession systems is large: as such the output from any one concession system will have negligible effects on price.

[14] This corresponds to cases where resource rents are not constant: situations where the resource price is either time or stock dependent are also consistent cases.

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

$$e_{it}^* = e_i^*. \tag{9}$$

Since biological growth, dispersal, and economic returns are patch-specific, the optimal policy will vary across patches. Equation 8 highlights that this policy depends on patch-specific net prices, growth, and dispersal and self-retention parameters.

We focus on policies with an interior solution - that is, those that are consistent with the sustainable management of the resource. This emphasizes the importance of ecological and economic fundamentals on the performance of the instrument, and is formally equivalent to assuming $g_i'(0) > \frac{p_i}{\delta \sum_j D_{ij} p_j}$ and $x_{i0} > (g_i')^{-1}\left(\frac{p_i}{\delta \sum_j D_{ij} p_j}\right)$ are satisfied, that is, marginal growth $g_i'(0)$ and initial stock level x_{i0} lie above minimum threshold values. In Section 3.1.2 we characterize the decentralized property rights case, and highlight that the resulting extraction levels are higher than the socially optimal levels: thus, in the decentralized reference setting, the resource is over exploited. We then show that limited-tenure concessions can overcome this over-exploitation problem.

3.1.2 Decentralized Perpetual Property Right Holders

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

$$\max_{\{e_{it}\}} \sum_{t=0}^{\infty} \delta^t p_i \left(x_{it} - e_{it}\right). \tag{10}$$

subject to the equation of motion (5). Following Lemma 1 in Kaffine and Costello (2011), in this uncoordinated benchmark setting, owner i will always harvest down to a residual stock level $\bar{e}_{it}$ that satisfies:

$$g_i'(\bar{e}_{it}) = \frac{1}{\delta D_{ii}}. \tag{11}$$

We thus assume that the decentralized situation correspond to an interior equilibrium outcome: this requires that $g_i'(0) > \frac{1}{\delta D_{ii}}$ and $x_{i0} > (g_i')^{-1}\left(\frac{1}{\delta D_{ii}}\right)$ be satisfied.

Thus, marginal growth $g_i'(0)$ lies above a minimum threshold value. This keeps the exposition as simple as possible, but our instrument can address cases where this does not hold. Moreover, as efficient policies are interior (see Section 3.1.1), the condition on the initial stock level is satisfied already.

At the equilibrium outcome, the owner takes other owners' behaviors as given and realizes that he will not be the residual claimant of any conservative harvesting behavior. Thus, he behaves as if any additional resource that disperses out of his patch will be lost (indeed it will be harvested by his competitors). This is why the only dispersal term to enter the optimal residual stock term is D_{ii}, the fraction of the resource that remains in his patch. We have $\bar{e}_{it} \leq e^*_{it}$ (with strict inequality as long as $D_{ii} \neq 1$): achieving social efficiency requires some kind of intervention or cooperation. Moreover, Equation (11) implies that $\bar{e}_{it} = \bar{e}_i$ for any time period.[15]

In our specification of decentralized property rights, we implicitly assume no trade in property rights. While this assumption accords with many real-world cases in which concessions are used, some elaboration is instructive. As we have shown, all owners have the incentive to extract at a rate that exceeds what is socially optimal. If trade were allowed, but consolidation was not, then this result would maintain - ownership of an area may change hands, but this would not dilute the incentive to overextract. However, if consolidation is allowed, there is in principle a solution in which one owner buys up all areas and can then implement the social planner's solution. For the remainder of this analysis we focus on the case in which consolidation is not allowed, so each property is managed by a different owner.

Unlike in Section 2, the game setting here is dynamic, owing to the stock growth over time. This raises several conceptual differences from a standard repeated game. First, the usual equilibrium concept for dynamic games is Markov perfect nash equilibrium (MPNE): there is no implicit assumption of agents' binding commitment about actions they will take at future dates (Reinganum and Stokey 1985) and the outcome is subgame perfect. Since the perpetual decentralized property rights setting can be considered a wholly uncoordinated setting, it makes sense to consider that the benchmark assumes no binding commitment and, as such, that the appropriate equilibrium concept in the benchmark is MPNE. Second, the trigger strategy equilibrium (another solution concept) is often criticized as it implicitly assumes that non-deviating agents can credibly commit to punish a deviating agent. This also implies that these agents would also punish themselves by using trigger strategies. But this is often regarded as not credible because the trigger strategy equilibrium is not renegotiation-proof (Heitzig, Lessmann, and Zou 2011).

[15] Kaffine and Costello (2011) show that the open loop and feedback control rules are identical.

3.1.3 Decentralized, Limited-Tenure Property Rights

In the final regime, and the one on which we focus in this paper, we assume that ownership over patch i is granted to a private concessionaire for a duration of $\mathcal{T}_i$ periods, to which we will refer as the "tenure block" for the concession. All concessionaires have the possibility of renewal provided that certain conditions are met. Indeed, it is the possibility of renewal that will ultimately incentivize the concessionaire to deviate from her (excessively high) privately-optimal harvest rate; we will leverage this fact to design concession contracts to induce efficient outcomes.[16] We begin by defining an arbitrary set of instrument parameters.

Definition 1. *The* Limited-Tenure Concession Instrument *is defined by, for any concessionaire i: a per-period "target stock," $\mathcal{S}_i$, a tenure period, $\mathcal{T}_i$, and a renewal probability $0 \leq f_i \leq 1$ which is the scalar probability of renewal conditional upon meeting the announced target stock.*

The concessionaire is allowed to extract as much of the resource as she wishes over her tenure block, and the regulator imposes only one rule on the concessionaire: 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) with probability f_i if and only if the stock is maintained at or above the target stock ($\mathcal{S}_i$) in every period. So, concession i will be renewed with probability f_i if and only if:

$$e_{it} \geq \mathcal{S}_i \qquad \forall t \leq \mathcal{T}_i - 1. \tag{12}$$

The renewal requirement is defined with respect to the stock level at the *end* of any given time period: the residual stock level in patch i at time period t (e_{it}) must lie above the target stock S_i. We allow for this instrument to be explicitly spatial ($\mathcal{S}_i \neq \mathcal{S}_j$). If the announced target stock $\mathcal{S}_i$ is not met then the probability of renewal is zero.

Beyond the enforcement of the concession contract, the regulator plays no role: all harvest decisions are made privately by the concessionaire. Because the regulator would like to replicate the social planner's solution (see Section 3.1.1), she must determine a set of target stocks in each area $\{\mathcal{S}_1, \mathcal{S}_2, ..., \mathcal{S}_N\}$, tenure lengths $\{\mathcal{T}_1, \mathcal{T}_2, ...\mathcal{T}_N\}$ and renewal probabilities $\{f_1, f_2, ...f_N\}$ (i.e., a $\{\mathcal{S}_i, \mathcal{T}_i, f_i\}$ triple to offer concessionaire i) that will incentivize all concessionaires to simultaneously, and

[16] While we continue to implicitly rule out trade in property rights, it is innocuous to allow trade in *concession contracts* (again, without consolidation) because the incentives facing the buyer would be identical to those facing the seller.

in every period, deliver the efficient level of harvest in all patches. We will restrict attention to tenure lengths satisfying $\mathcal{T}_i = T$, $\forall i$.[17]

We will show that, if designed properly, limited-tenure concessions can be used to induce concessionaires to manage resources in an efficient manner. Agents may, or may not, comply with the terms of the concession contract. If all N concessionaires choose to comply with the target stocks in every period of every tenure block, we refer to this as *cooperation*. All owners will then earn an income stream in perpetuity. Instead, if a particular owner i fails to meet the target stock requirement (i.e, in some period she harvests the stock below $\mathcal{S}_i$), then, while she will retain ownership for the remainder of her tenure block (and thus be able to choose any harvest over that period), she will certainly not have her tenure renewed. In that case, owner i's payoff will be zero every period after her current tenure block expires. Thus, the instrument raises a trade-off for each concessionaire who chooses whether to cooperate or to defect. 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.[18]

3.2 Cooperation vs. Defection

We now characterize (i) the payoffs that each concessionaire could achieve under cooperation, and (ii) the concessionaires' best defection strategies. We first consider that all N concessionaires cooperate and thus comply with the target stocks in every period of every tenure block. Provided they do not exceed the target stock then concessionaire i's expected payoff is:

$$\Pi_i^c = p_i \left[x_{i0} - \mathcal{S}_i + \sum_{t=1}^{T-1} \delta^t \left(x_i^* - \mathcal{S}_i \right) + \sum_{l=1}^{\infty} \left(f_i \right)^l \left(\sum_{t=lT}^{(l+1)T-1} \delta^t \left(x_i^* - \mathcal{S}_i \right) \right) \right]. \qquad (13)$$

where x_{i0} is the (given) starting stock and $x_i^* = \sum_j D_{ji} g(\mathcal{S}_j)$. Because it is fundamental to the externality we examine, the role of resource migration deserves a few remarks. First, whether a player can achieve $e_{it} \geq \mathcal{S}_i$ depends on what the other players do. Of course, in (at least pure strategy) equilibria, agents rationally expect

[17] Since concessionaires are heterogeneous, tenure lengths could be heterogeneous. In order to limit complexity, 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 concessionaires' incentives to cooperate (see expression 18 in Section 4).

[18] This rule is irrelevant: as we later show, if everyone defects, the resource is driven extinct.

others to follow the equilibrium strategy, and this dependence is not an issue. Second, a deviating agent considers only D_{ii}. This is because, agent i knows that agent j will make sure that $e_{jt} \geq S_j$ regardless of the amount migrating from patch i to patch j. Hence, no matter what agent i does, the amount migrating from patch j to patch i remains at $D_{ji} g(\mathcal{S}_j)$.

We turn to the characterization of the concessionaires' best defection strategies. If concessionaire i defects during an arbitrary tenure block k and all other concessionaires follow their equilibrium strategies (that is, they cooperate), we have:[19]

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

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

$$g_i'(\bar{e}_i) = \frac{1}{\delta D_{ii}} \quad \textit{with } \bar{x}_i = D_{ii} g(\bar{e}_i) + \sum_{j \neq i} D_{ji} g(\mathcal{S}_j) > \bar{e}_i.$$

When marginal growth $g_i'(0)$ is sufficiently low in area i, a concessionaire who decides to defect *sometime* during tenure block k, will completely mine the resource in his patch at every period of the tenure block. By contrast, when marginal growth is high enough, this defecting concessionaire will (1) choose the non-cooperative level of harvest (see Section 3.1.2) up until the final period of the tenure block and (2) then completely mine the resource.[20] Either way, the resource is completely mined in that patch by the end of the tenure block. The best defection strategy depends neither on the tenure block, k, nor on the renewal probabilities, and so we have:

Lemma 1. *Suppose the regulator can choose the renewal probabilities to maximize the likelihood of cooperation. Then she chooses $f_i = 1$ for any concessionaire i.*

Combined with Proposition 1, this feature simplifies the characterization of equilibrium strategies. We thus consider now that $f_i = 1$ for any concessionaire i. The present value of owner i's defection payoffs is:

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

[20] 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.

$$\Pi_i^d = p_i \left[x_{i0} - \mathcal{S}_i + \sum_{t=1}^{(k-1)T-1} \delta^t \left(x_i^* - \mathcal{S}_i \right) + \delta^{(k-1)T} \left(x_i^* - \bar{e}_i \right) + \sum_{t=(k-1)T+1}^{kT-2} \delta^t \left(\bar{x}_i - \bar{e}_i \right) + \delta^{kT-1} \bar{x}_i \right] \tag{14}$$

Patch owner i's defection payoffs during tenure block k is given by (1) the profit obtained while abiding by the target stock prior to the k^{th} tenure block (first two terms on the right-hand side of (14)), and (2) the profit from non-cooperative harvesting during tenure block k (the third and fourth terms on the RHS of (14)), until finally extracting all the stock in the final period of the k^{th} tenure block, $kT-1$ (the fifth and final term on the RHS of (14)). We will extensively use the defection strategy in what follows. We next turn to the conditions ensuring cooperation.

4 Conditions for Cooperation

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

4.1 The emergence of cooperation

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

Lemma 2. *A necessary condition for social optimality is that the regulator announces:* $\mathcal{S}_1 = e_1^*$, $\mathcal{S}_2 = e_2^*$,..., $\mathcal{S}_N = e_N^*$, *where* e_i^* *is given in Equation 8.*

Lemma 2 relies on 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 optimally 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 either complies with the target (and the stock is inefficiently high) or defects and reaches an inefficiently low target stock. Thus, Lemma 2 provides the target stocks that must be announced. We can now restrict attention to the target stocks $\mathcal{S}_i = e_i^*$ $\forall i$: concessionaire i's compliance requires that $e_{it} \geq e_i^* \; \forall t$, so she must never harvest below that level. We show that, while concessionaire i is free to choose $e_{it} > e_i^*$ she will never do so.

Proposition 2. *If concessionaire i chooses to cooperate, she sets $e_{it} = e_i^* \; \forall i, t$.*

Proposition 2 establishes that, if it can be achieved, cooperation involves each concessionaire leaving precisely the socially-optimal residual stock in each period. We proceed as follows. We characterize the conditions ensuring that any given concessionaire i lacks incentives to defect from the strategy characterized by Proposition 2 when all other concessionaires follow this strategy.[21] In any tenure block, the decision facing concessionaire i is whether or not to comply with the target stock requirement in each period. When all other concessionaires follow the strategy characterized by Proposition 2, one simply calculates her payoff from the best defection strategy (see Proposition 1) and compares it to her payoff from the cooperation strategy. We define concessionaire i's *willingness-to-cooperate* by:

$$W_i \equiv \Pi_i^c - \Pi_i^d. \tag{15}$$

Reminiscent of Folk-Theorem results in repeated games (see Mailath and Samuelson (2006)), 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.

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

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

Condition 16 is the analog to Condition 4, which was derived in the simple case of private provision of public goods. Proposition 3 shows that the gains from cooperation to concessionaire i ($\delta x_i^* - e_i^*$) must be large enough compared to defection gains ($\delta \bar{x}_i - \bar{e}_i$): we get cooperation forever.[22] Consider that concessionaires are patient, thus the discount factor δ is high: The right-hand side of Condition 16 gets close to zero, and the left-hand side to $x_i^* - e_i^*$, so as long as the solution to the optimal spatial problem is interior, the condition holds. By contrast, when concessionaires are impatient (the discount factor gets close to zero), as $e_i^* > \bar{e}_i$, cooperation never arises.

[21] These conditions ensure that the socially optimal outcome constitutes an equilibrium outcome.

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

These cases are just examples: there are cases (depending on spatial parameters) where Condition 16 holds without assuming sufficiently patient concessionaires.

While the stock dynamics make our model more complicated than a repeated game, insights from the repeated game literature can still provide intuition for our results. Here, setting $T_i = 1$ relaxes the incentive constraint the most. This is comparable to the perfect monitoring setup in repeated games, so the optimal penal code applies (Abreu 1988). Hence, as soon as one concessionaire deviates, she should be punished as severely as possible. In the current setup, the most severe punishment is to kick the concessionaire out of the game for the rest of time.

We show that our concession instrument can lead to efficient extraction across space and time in perpetuity.[23] But this relies on a relatively strict enforcement system (an owner who defects is not renewed). Because the welfare gains from cooperation vs. non-cooperation are potentially large, less stringent systems might 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. Our analysis highlights that, even without accounting for additional incentives (financial penalties), limited-tenure concessions have attractive practical appeal.[24]

How does limited-tenure compare to alternatives that rely on self-punishment? The trigger strategy equilibrium is often criticized as it implicitly assumes that non-deviating agents can credibly commit to punish a deviating agent. This also implies that these agents will also punish themselves by using trigger strategies. But this is typically non-credible, as a trigger strategy equilibrium is not renegotiation-proof. In contrast, under our proposed instrument, the non-deviating agents are not required to punish themselves; that is, rather than being punished by other players, a deviating player is simply kicked out of the game. Moreover, we can show that there is a set of tenure durations for which a wider set of conditions ensure that the social optimum is implemented as an equilibrium outcome under our instrument (compared to under the use of trigger strategies).[25]

We conclude this section by discussing some salient cases that can be addressed by our instrument. First, the polar case where social efficiency requires $e^*_{it} = 0$

[23] Under our instrument, there might exist equilibria in which all agents extract more than the amount specified by the concession contract. It is straightforward to show that there is a set of tenure durations for which such candidates cannot constitute an equilibrium provided there is at least one patch i which growth-related parameter α_i is large enough (formal proof available upon request).

[24] Financial penalties may be infeasible in developing countries, as financial constraints may be tight. As the effect of financial capacity on natural resource management is ambiguous (Tarui (2007)), the concession instrument avoids potential problems related to the use of monetary devices.

[25] Formal details are available upon request.

$\forall t \geq 0$ (that is, harvesting the entire stock) in some patches can be addressed by our instrument: the marginal incentives for these patches in the decentralized situation also correspond to this case. Second, the other polar case, where $e^*_{it} = x_{it}$ $\forall t \geq 0$ (where it is optimal to forbid extraction) in at least one patch i, cannot be addressed by our instrument or by any concession instrument. To implement the socially optimal path, this would require combining our instrument with a side-payment scheme. However, in cases where there exists a time period t_0 such that $e^*_{it} = x_{it}$ $\forall t \leq t_0$ and $e^*_{it} < x_{it}$ thereafter for any patch i, one can design a concession instrument inducing the socially optimal path starting at $t = t_0 + 1$. It would be defined as: $\forall t \leq t_0$ we have $S_{it} = \bar{S}_i < x_{it}$ (where this target level is characterized depending on the fundamentals of the setting) and $\forall t \geq t_0 + 1$ we have $S_{it} = e^*_i$.

4.2 Effects of Patch-Level Characteristics

Patch-level characteristics will affect a concessionaire's payoffs and therefore play a role in the decision of whether to defect or cooperate. The fact that these characteristics may also affect the announced target stocks further complicates the analysis. We next examine the effects of price, growth, and dispersal on the concessionaire i's *willingness-to-cooperate*, defined by Condition (15). As a parameter changes, we trace its effects through the entire system, including how it alters others' decisions. Assuming that the willingness to cooperate is initially positive, the impact of prices $\{p_i, p_j\}$ is as follows: Concessionaire i's willingness-to-cooperate, W_i, is increasing in p_i, but is ambiguous in the price of the adjacent area, p_j, and depends on the degree of the connection between patches.

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

Finally, we provide cases in the Appendix where the cooperation incentives are increasing in self-retention, D_{ii}, but its impact is mixed as it affects the resource stock under defection and cooperation. W_i is increasing in D_{ji} for reasons similar to those driving comparative statics on α_j. In contrast, a higher emigration rate (D_{ij}) reduces the incentives to cooperate: defection incentives are not altered much (since concessionaire i harvests the entire stock under defection), but cooperation incentives are reduced because the regulator will instruct concessionaire i to reduce her harvest under a larger D_{ij}.

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

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

These results provide insight about how the strength of i's cooperation incentive depends on parameters. Whether this incentive is sufficiently strong to induce cooperation (i.e. whether $W_i > 0$) remains to be seen. We focus on resource dispersal. If the resource was immobile, the patches would not be interconnected, and private property owners with secure property rights would harvest at a socially optimal level in perpetuity. Dispersal undermines this outcome and induces a spatial externality which leads to overexploitation. Thus, the nature and degree of dispersal will play an important role in each concessionaire's cooperation decision.

Dispersal is characterized by the NxN matrix whose rows sum to something less than or equal to 1 ($\sum_j D_{ij} \leq 1$). There are N^2 free parameters describing 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 defects, she will optimally do so by considering only D_{ii}, thus ignoring all other $N^2 - 1$ elements of the dispersal matrix. We can thus assess the effect of spatial parameters on the emergence of cooperation. We show that a high degree of self-retention in all patches – that is a situation with low migration rates – is sufficient to ensure cooperation.

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

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

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

$$p_i \sum_{j \neq i} D_{ji} g(e_j^*) < \sum_{j \neq i} D_{ij} p_j g'(e_i^*) e_i^*. \tag{17}$$

Proposition 5 establishes that if the resource is highly mobile (sufficiently low self-retention rates), then cooperation might be destroyed. This result relies on the fact that economic benefits mainly depend on resource immigration. Condition (17) compares concessionaire i's cooperation benefits due to incoming resources and the sum of benefits others may get from the resource migrating from patch i.

4.3 Effect of tenure duration

Thus far we have focused on inherent features of the system as a whole that affect a concessionaire's incentives to cooperate or defect. But Condition (16) also depends on the tenure length T. This is a policy issue for a concession regime to be successful. We now focus 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. Costello and Kaffine (2008) found that longer tenure duration indeed increased the likelihood of sustainable resource extraction in limited-tenure (though aspatial) concessions. So at first glance, we might expect a similar finding here. In fact, we find the opposite:

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

Proposition 6 seems to contradict basic intuition: if tenure duration is long, it is impossible to achieve efficient extraction of a spatially-connected resource by using our instrument. But upon deeper inspection this result accords with economic principles, due to defection incentives driven by spatial externalities, while such effects are absent in Costello and Kaffine (2008). Consider the case of very long tenure duration - in the extreme, when tenure is infinite, gains from defection always outweigh gains from cooperation. The promise of renewal has no effect on incentives, so each concessionaire acts in his own best interest, which involves the defection path identified in Proposition 1. Proposition 6 also holds in an extended version of the instrument, where the regulator can (with some probability $\Psi < 1$) terminate tenure immediately upon defection (rather than waiting until the end of the tenure block in which defection occurs). This extended version is described in sub-section 5.1.

Short tenure duration harbors two incentives for cooperation: First, when tenure is short, the defection payoff is 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 does the current tenure block. This result obtains because the spatial externality drives a wedge between the privately optimal decision and the socially optimal one. In fact, we can characterize a threshold tenure length for which concessionaire i will defect if $T_i > \bar{T}_i$, and owner i will cooperate otherwise:

$$\bar{T}_i = 1 + \frac{\ln\left(\frac{\delta(\bar{x}_i - x_i^*) + e_i^* - \bar{e}_i}{\delta \bar{x}_i - \bar{e}_i}\right)}{\ln(\delta)} \tag{18}$$

Thus, cooperation is sustained by assigning to all N concessionaires a threshold value, which we summarize as follows:

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

$$\delta x_i^* - e_i^* > (1-\delta)\left(\delta \bar{x}_i - \bar{e}_i\right); \tag{19}$$

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

Condition (19) is a restatement of Proposition 3 for a tenure period $T = 2$. Thus, we know that a tenure period of 1 will guarantee cooperation. Since $\bar{T} = \min_i\{\bar{T}_i\}$ depends on patch level characteristics, we briefly examine its dependence on patch, and system-level characteristics in Section B of the Appendix.

5 Robustness checks

To maintain analytical tractability, and to sharpen the analysis, we have relied on a number of simplifications. Here we discuss the issue of stock assessment and monitoring, then examine the consequences of three noteworthy assumptions. Specifically, we discuss the effect of a finite horizon on incentives to cooperate, then the cases of, respectively, stock-dependent costs and density-dependent dispersal.

5.1 Stock assessment and monitoring

We assume that the regulator can monitor the stock to verify compliance with the terms of the concession contract. In practice, stock assessment may be difficult to implement, and the cost of monitoring may thus prove important. Several points are worth highlighting. First, Proposition 6 also holds in an extended version of the instrument, where the regulator can (with some probability $\Psi < 1$) terminate tenure immediately upon defection (rather than waiting until the end of the tenure block in which defection occurs).[26] Indeed, the best defection will retain the features of Proposition 1: $\bar{e}_{it} = \bar{e}_i(\Psi) > 0$ at every period but the last one, and $\bar{e}_{ikT-1} = 0$ (as long as $1 - \Psi$ is large enough so that $\bar{e}_i(\Psi) > 0$ holds). Since cooperation payoffs remain unchanged, results in Proposition 3 and thus Proposition 6 remain valid under this extension. Parameter Ψ could also reflect stock assessment uncertainty (so Ψ is the probability of correct assessment). Then the instrument is robust to imperfect stock assessment (when Ψ is large enough). On the other hand, if it denotes the probability that stock assessment is actually implemented, then the expected monitoring cost would decrease as the tenure length increases. Thus, when it is costly to frequently monitor users' actions, and to revoke and reallocate rights upon defection, there is a trade-off for tenure duration: Long tenure duration might result in defection, while short duration might entail higher monitoring costs.[27]

Second, several contributions suggest that regular stock assessment is a mandatory part of a well-designed concession system, even if it is based on extraction levels. In successful systems an annual stock assessment is carried out by technical consultants approved by the government and paid by concession members.[28] This requirement is further supported by Hilborn et al. (2005): successful concession systems based on extraction levels tend to engage in active research programs funding stock assessments. Thus, for a system to be effective, proper stock assessment is mandatory, whether the system is based on extraction or on (residual) stock requirements.

Moreover, endogenous enforcement might be strengthened by parameters inducing persistent cooperation over time, particularly when monitoring involves capital expenditures.[29] Enforcement issues may be driven by lack of legitimacy or the "need" for profit versus risk of deterrence. In developing countries this motivation might be greater than in developed ones; this might underscore enforcement issues. Yet, initiatives like community-based concessions might improve legitimacy while reducing

[26]We maintain the assumption that, at the last period of the tenure block, the regulator can terminate tenure immediately upon defection with probability one.

[27]The same conclusion holds in the public good setting when monitoring is costly.

[28]See Wilen et al. (2012) for a discussion.

[29]Concession rights might strengthen endogenous enforcement, and this could be rewarded via management certification, which may in turn provide improvements in market access. Thus, certifications might decrease transaction costs and strengthen agents' monitoring activities; both mechanisms would plausibly ease the conditions under which our instrument induces the efficient outcome.

monitoring costs.[30] These institutional arrangements are receiving increasing attention in developing countries. Since participation in the organization of the concession instrument can contribute to its legitimacy, such concessions might be interesting to increase enforcement in such areas. Finally, real-world cases suggest that science-based stock assessment is an integral part of the property rights system, which makes it less onerous for managers to monitor stocks and assess patch-specific characteristics. Cooperation between communities and government might help to decrease the cost of stock assessment, providing incentives for engagement in assessment practices (Hilborn et al. (2005)). Indeed, it allows increasing interactions between concession owners and public-sector scientists, who might contribute to stock assessment, thus decreasing the assessment cost in return for access to the data collected.

Finally, if stock assessments require a fixed cost each year, they also influence the planner's optimized payoff, but will not affect her optimal choice of residual stock (Section 3.1.1). This will also be the case for concessionaires under our proposed instrument: their optimized payoffs will be affected, but their optimal choice to co-operate/defect will not. Monitoring costs will affect the agents' optimized payoff, but they will not affect the ability of the instrument to act as an effective cooperation device.

5.2 The case of a finite horizon

In this analysis, concessionaires must trade off a finite single tenure block against an infinite number of renewed tenure blocks. It raises the question of whether the instrument is still effective at inducing cooperation when the horizon is finite. Suppose time ends after K tenure blocks where $1 < K < \infty$ after which all concessionaires' payoffs are zero. We briefly explain here why cooperation is subgame perfect under the finite horizon problem, and that this requires more stringent conditions than under an infinite horizon.

Specifically, it can be proved that the instrument then induces cooperation for the first $K-1$ tenure blocks.[31] Thus, the time horizon need not be infinitely long for our instrument to be effective: yet this requires more stringent conditions. Indeed, a condition equivalent to the one provided in Proposition 3 characterizes the incentive constraint. The gains from defection remain the same than in the infinite horizon setting, while the gains from cooperation become more complex. Concessionaires

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

[31] Formal details rely on backward induction arguments and are available upon request.

anticipate that they will not be renewed at the end of the final tenure block: they thus follow the cooperative strategy during the first tenure blocks, then they *all* defect in a similar manner than in the infinite-horizon case (they choose a positive residual stock before mining the resource in the final period). The cooperation payoffs during the entire process are now lower due to the increase in the defection payoffs in the final period. In other words, shorter time horizons require more stringent conditions for cooperation to be effective: longer time horizons (not to be confused with longer tenure durations) are most effective.

5.3 Stock-dependent costs

So far, we assume that extraction costs are linear in the amount extracted. Here we discuss how this assumption can be relaxed. Concessionaire i's period-t payoffs then become:

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

where $c_i'(s) < 0$ is continuously differentiable (see Reed (1979) for an early treatment of stock-dependent costs). We now explain briefly why the logic of Proposition 3 remains valid here. The proof relies mainly on two arguments.[32]. First, the best defection strategy does not depend on the tenure block considered. Second, for the tenure block during which defection occurs, patch owner i's best defection strategy remains qualitatively the same as in Proposition 1: He chooses the non-cooperative level of harvest up until the final period of the block, and he then mines the resource by eventually harvesting down to level $c_i^{-1}(p_i)$.[33] Thus, even though the characterization of the best defection strategy differs, and so the conditions ensuring the emergence of cooperation differ from Conditions (16), the qualitative conclusion of Proposition 3 still remains valid.

There is one interesting difference though. When costs are stock independent, an agent (say i) who would choose to defect would eventually drive the resource to extinction in his own patch. By contrast, if costs do depend on stock levels, agent i does not drive the resource to extinction if he chooses to defect, but he eventually harvests it down to level $c_i^{-1}(p_i) > 0$. This has a negative effect on this agent's incentives to defect by lowering the potential benefits from defection. The assumption of stock-dependent costs, through its negative effect on defection incentives, would make cooperation easier to sustain compared to the case of stock-independent costs.

[32]Full details are available upon request.

[33]These properties rely on backward reasoning arguments.

5.4 Stock dependent dispersal

We assume so far that the dispersal process does not depend on residual stock levels. We now relax this assumption. Thus, we define for any patch i the law of motion as $x_{it+1} = \sum_j D(e_{jt})g_j(e_{jt})$ which models density-dependent dispersal, and where $D(e_{it})$ denotes the difference between self-retention and dispersal rate.

In this amended version of the model, following Costello and Polasky (2008) it is easily checked that the socially-optimal policy still remains time and state independent. Moreover, the characterization of the best defection strategy follows from backward induction arguments as in Section 3.2: assuming defection occurs at tenure $k+1$, we obtain $e_{i(k+1)T-1} = 0$ and then, for any preceding time period t in tenure $k+1$, we have $e_{it} = \hat{e}_i$ satisfying

$$-1 + \delta \left[D'(e_{it})g_i(e_{it}) + D(e_{it})g_i'(e_{it})\right] = 0$$

This condition highlights two effects: a direct effect on marginal productivity, which might result in higher or lower defection strategy, and an indirect effect on dispersal, which tends to increase benefits from higher in-migration if one assumes negative density-dependent dispersal. Specifically, we deduce:

$$g_i'(\hat{e}_i) = \frac{1 - \delta D'(\hat{e}_i)g_i(\hat{e}_i)}{\delta D(\hat{e}_i)} \tag{20}$$

Compared to the case of density-independent dispersal, it is more difficult to induce cooperation under negative density-dependent dispersal.

Proposition 8. *Denote $D_{ii} \equiv D(\hat{e}_i)$ and consider $\hat{e}_i$ the solution to condition (20). Then $\hat{e}_i < \bar{e}_i$ where $\bar{e}_i$ denotes agent i's best defection strategy under density-independent dispersal when self-retention rate in patch i is given by D_{ii}. The defection payoff increases, and the conditions for cooperation becomes more stringent under density-dependent dispersal.*

Since the optimal defection strategy yields higher payoffs under density-dependent dispersal, it becomes more difficult to sustain cooperation.

6 Comparison with other potential policies

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

One might consider alternative concession approaches, though a full comparison is beyond the scope of this paper. One candidate is to consider concessions with renewal based on maximum total extraction. The characterization of the socially optimal paths obtained in Section 3.1.1, together with the characterization of the best defection path in Proposition 1, suggest that this instrument would not achieve the socially optimal outcome. Even if total extraction requirements are satisfied by the end of the tenure, it will induce over-harvest in certain time periods. Thus, it cannot ensure that the socially optimal outcome is implemented at any time period.

Second, consider that renewal is based on the maximum total extraction in any time period. This is similar to our proposed system, except that the tenure renewal requirements is based on extraction target levels every time period, rather than a target stock. If one focuses on the capacity to induce the socially optimal outcome, then the conditions under which it is effective are equivalent to those related to our instrument. By the identity $h_{it} = x_{it} - e_{it}$, one could choose either extraction or residual stock as the main defining variable (given the state of the system (x_t) one derives from the other). Moreover, as discussed in Section 5.1, both instruments require regular stock assessment.

Third, consider policies that employ property rights over the resource rather than over space. This approach induces challenges for spatial resources because biological growth, dispersal, and economic returns are patch-specific, and the optimal policy will thus vary across patches. Equation 8 reveals that the optimal policy depends on patch-specific net prices, growth, and dispersal and self-retention parameters. So the efficient outcome is spatially explicit, while using property rights over the resource results in a non-spatial instrument. Thus, it cannot achieve the first best, unlike our proposed instrument. Furthermore, as explained in Section 5.1 it is not clear that such system would be less demanding in terms of the related monitoring costs if the manager wants this policy to be as effective as possible.[34]

While the size of concessions is not endogenously chosen here, this dimension might be part of the manager's decision. If size is somehow related to biological productivity, then the findings from Section 4.2 suggest that variations in the size of connected patches may have complex effects. Indeed, agent i's willingness to cooperate increases as the size of an adjacent property increases, but the effect of an

[34]See Wilen et al. (2012) for other advantages of spatially explicit instruments.

increase in the size of agent i's own property on his incentives to do so is ambiguous. Such a policy would then have to account for a variety of direct and indirect effects. This will raise many new questions about design and effectiveness.

While we have implicitly ruled out consolidation of all areas to a sole owner, it is possible to consider tradeable versions of our property rights approach. There are two ways to think about tradeability. First, one could consider transferability within a concession regime where the "buyer" is bound by the same concession terms as was the "seller". This kind of transferability is innocuous because all extraction incentives remain unchanged. Second, we could consider perpetual, property rights with transferability. If properties are not consolidated, then again, no change in incentives would arise. But if one agent was to acquire and consolidate all properties, then she could act as a sole owner and implement the first best policy derived in Section 3.1.1. Without complete consolidation, some spatial externalities would remain between non-consolidated properties, and inefficiencies would still result from decentralized management.

7 Conclusion

We have analyzed the ability of limited-tenure concessions to induce socially-efficient private provision of a class of public goods. We first analyzed a stylized public goods contribution setting and then turned to a more complicated natural resource extraction setting with resource growth, mobility, and heterogeneity across space. That limited-tenure concessions can achieve first-best private contributions may be surprising, as it does not rely on any transfers or side-payments,[35] though it does accord with many real-world institutions for managing natural resources and public goods. The instrument works effectively by offering the promise of concession renewal, and therefore the promise of future benefits of the public good, but only if socially-optimal behavior has been undertaken in the past. Thus, if well-designed, concessionaires will be incentivized to adhere to efficient contribution, and to thus achieve renewal, rather than to under-contribute in the short run, and thus fail to achieve renewal. Contrary to an initial intuition, longer tenure actually induces underprovision. This implies that there is an optimal tenure length, which we derive in the paper.

Several extensions remain; we discuss some of the salient ones for common-pool resources. There could be imperfect (incomplete) information, or the resource growth could be stochastic. As long as patches are symmetric regarding the anticipated effects, we expect no drastic change in the qualitative results. The regulator's in-

[35]This feature of our instrument consequently yields an advantage over market-based instruments.

centives in offering concessions may also be an interesting issue. In this setting, the regulator could be viewed as a Stackelberg leader. The focus was on identifying design parameters that induce cooperation. A next step could involve introducing different regulators' objectives. Finally, depending on the ecosystem dynamics, there could be different timing of growth. This reduces model tractability and neither renders our results moot nor obviously makes the analysis more realistic.

Overall, the results suggest that limited-tenure concessions may be one important institutional tool to help achieve socially-optimal private provision of public goods, all while allowing concessionaires the autonomy to make decentralized decisions, which is important for the acceptability of the instrument. The analysis in this paper suggests that concessions may not only have attractive intuitive appeal for managing natural resources and other collective goods, but if designed with care, they could be theoretically grounded in economic efficiency.

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Appendix

Proof of Proposition 1

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

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

Using the first order condition yields $\bar{e}_{ikT-1}=0$ and, moving backward, at period $T-2$, this concessionaire's problem becomes:

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

Using the first order condition and $\bar{e}_{ikT-1}=0$, we have $\delta D_{ii}g'(\bar{e}_{ikT-2})=1$ since $\bar{e}_{ikT-2}=0$ is ruled out by the lower bound on $g'(0)$, and $\bar{e}_{ikT-2}=x_{ikT-2}$ is ruled out if $x_{ikT-2}>(g')^{-1}\left(\frac{1}{\delta D_{ii}}\right)$ holds. Using again backward induction highlights that any $\bar{e}_{it}$ ($(k-1)T\leq t\leq kT-3$) is characterized by the same condition provided that $x_{it}>(g')^{-1}\left(\frac{1}{\delta D_{ii}}\right)=\bar{e}_i$. We have, by definition of $\bar{e}_i$ and concavity of $g(.)$, that $g(\bar{e}_i)>\bar{e}_i g'(\bar{e}_i)=\frac{\bar{e}_i}{\delta D_{ii}}$ which implies $D_{ii}g(\bar{e}_i)>\frac{\bar{e}_i}{\delta}\geq\bar{e}_i$ for $\delta\in]0,1]$, and we deduce that $x_{it}>\bar{e}_i$ for any tenure block but the first one. Even if concessionaire i defects initially, since $x_{i0}>(g')^{-1}\left(\frac{p_i}{\delta\sum_j D_{ij}p_j}\right)>(g')^{-1}\left(\frac{1}{\delta D_{ii}}\right)$ by assumption, the same conclusion follows. The second case follows from similar arguments because of the upper bound on $g'(0)$.

Proof of Lemma 1

Let us consider the case of concessionaire i. If this concessionaire chooses to defect in tenure block k, then his payoff from cooperation and his payoff from defection are the same during the first $k-1$ tenure blocks. Then, during tenure block k, his payoff from defection does not depend on the renewal probability. By contrast, from tenure block k on, his payoff from cooperation does increase as f_i increases (due to expression 13). Thus, a direct implication is that raising f_i always increases the likelihood that concessionaire i chooses to cooperate.

Proof of Proposition 2

If there is t during which concessionaire i chooses $e_{it}>e_i^*$: e_{it} is strictly profitable only if:

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

Simplifying this inequality, we obtain:

$$\delta D_{ii}\left(g\left(e_{it}\right)-g\left(e_i^*\right)\right)>e_{it}-e_i^*. \tag{21}$$

Since $g(.)$ is continuously differentiable and increasing, there exists $e_i\in]e_i^*,e_{it}[$ such that $g\left(e_{it}\right)-g\left(e_i^*\right)=\left(e_{it}-e_i^*\right)g'(e_i)$ and we rewrite expression 21 as follows:

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

Since $g(.)$ is strictly concave we have $e_i^*<e_i<\bar{e}_i$, which is a contradiction (since $e_i^*\geq\bar{e}_i$ as explained in subsection 3.1.2). This implies that $e_{it}=e_i^*$ for any time period t.

Proof of Proposition 3

If concessionaire i deviates during tenure $k+1$ then his payoff is $\Pi_i^d = p_i A$, where :

$$A = \left[x_{i0} - e_i^* + \frac{\delta(1-\delta^{kT-1})}{1-\delta} (x_i^* - e_i^*) + \delta^{kT} (x_i^* - \bar{e}_i) + \frac{\delta^{kT+1}(1-\delta^{T-2})}{1-\delta} (\bar{x}_i - \bar{e}_i) + \delta^{(k+1)T-1} \bar{x}_i \right].$$

Now, using Condition (13), we compute $\Pi_i^c - \Pi_i^d = p_i B$, with:

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

The conclusion follows from Equality (22).

Proof of Proposition 4

We prove that the concessionaire does not defect from the initial period until the end of the first tenure. From the proof of Proposition 3 (using the expression (22) when $k = 0$) we know that:

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

When D_{ii} gets arbitrarily close to one, we deduce that $\bar{e}_i$ gets arbitrarily close to e_i^*, so that $\bar{x}_i$ gets arbitrarily close to x_i^*. We can deduce that $\Pi_i^c - \Pi_i^d$ gets arbitrarily close to:

$$\frac{p_i}{1-\delta} \left[\delta x_i^* - e_i^* - \left(1-\delta^{T-1}\right) (\delta x_i^* - e_i^*) \right] > 0 \tag{23}$$

Thus, for $D_{ii} = 1$ we know that $\Pi_i^c - \Pi_i^d > 0$ which, by a continuity argument, implies that this deviation is not profitable for sufficiently large (but less than one) values of self retention.

Proof of Proposition 5

Using Proposition 3, we know that concessionaire i would defect if $\delta x_i^* - e_i^* < \left(1-\delta^{T-1}\right)(\delta \bar{x}_i - \bar{e}_i)$ holds. The right hand side increases as T increases: its derivative is $-\delta^{T-1} ln(\delta) (\delta \bar{x}_i - \bar{e}_i) > 0$ since $ln(\delta) < 0$ and $\delta \bar{x}_i - \bar{e}_i$ is positive.[36] 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 $\delta x_i^* - e_i^* = \delta \left[\sum_{j \neq i} D_{ji} g(e_j^*) - \sum_{j \neq i} D_{ij} \frac{p_j}{p_i} g'(e_i^*) e_i^* \right]$ and thus, when Condition 17 holds, then $\delta x_i^* - e_i^*$ is negative.

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

Proof of Proposition 6

Assume that any concessionaire $j \neq i$ follows the cooperation path; we analyze concessionaire i's incentives to defect. According to Proposition 1, his payoff from the best defection strategy is equal to Π_i^d and we prove that $\Pi_i^c - \Pi_i^d \leq 0$ for large enough values of T. Using the proof of proposition 3 we have:

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

When T gets large, the term between brackets gets close to

$$\left[\delta x_i^* - e_i^* - (\delta \bar{x}_i - \bar{e}_i)\right]. \tag{24}$$

Now, we obtain $x_i^* - \bar{x}_i = D_{ii}(g(e_i^*) - g(\bar{e}_i)) < D_{ii} g'(\bar{e}_i)(e_i^* - \bar{e}_i)$ and $[\delta D_{ii}(g(e_i^*) - g(\bar{e}_i)) - (e_i^* - \bar{e}_i)] < \frac{p_i}{1-\delta}[\delta D_{ii} g'(\bar{e}_i) - 1](e_i^* - \bar{e}_i) = 0$ and we conclude that (24) is negative. A continuity argument implies that $\Pi_i^c - \Pi_i^d \leq 0$ for sufficiently large values of T.

Proof of Proposition 7

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

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

Since $\bar{e}_i$ and e_i^* do not depend on the value of $\bar{T}_i$ we can differentiate with respect to T and we obtain $\delta^{T-1} \frac{ln(\delta)}{1-\delta}(\delta \bar{x}_i - \bar{e}_i) < 0$ since $ln(\delta) < 0$ as $0 < \delta \leq 1$ and $\delta \bar{x}_i - \bar{e}_i$ is positive (as shown in the proof of Proposition 5). Thus this function is decreasing and continuous in 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 it has a positive value when $T = 2$ then $\bar{T}_i$ is uniquely defined and $\bar{T}_i > 1$.[37] Then, the proof of Proposition 4 implies 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:

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

It is positive by Assumption (19), which implies $\bar{T}_i = 1 + \frac{ln\left[\frac{\delta \bar{x}_i - \bar{e}_i - (\delta x_i^* - e_i^*)}{\delta \bar{x}_i - \bar{e}_i}\right]}{ln(\delta)}$ is well defined. This concludes the proof since $\bar{T} = \min_i \bar{T}_i$ qualifies as the appropriate threshold value.

Proof of Proposition 8

Negative density-dependent dispersal implies that $D'(.) < 0$ holds, and we conclude from (20) that $g_i'(\hat{e}_i) > g_i'(\bar{e}_i)$ which, due to concavity of the growth function, allows to conclude the proof.

[37] As $\bar{T}_i$ actually takes on discrete values, the proof implies that $\bar{T}_i$ is at least equal to 2.

Sections 4.2 and 4.3

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

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

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

$$\frac{d\bar{x}_i}{d\theta_i} = \frac{\partial \bar{x}_i}{\partial \bar{e}_i} \cdot \frac{\partial \bar{e}_i}{\partial \theta_i} + \frac{\partial \bar{x}_i}{\partial \theta_i} + \sum_{j \neq i} \frac{\partial \bar{x}_i}{\partial e_j^*} \cdot \frac{\partial e_j^*}{\partial \theta_i}; \quad \frac{d\bar{x}_i}{d\theta_j} = \frac{\partial \bar{x}_i}{\partial \theta_j} + \sum_{l \neq i} \frac{\partial \bar{x}_i}{\partial e_l^*} \cdot \frac{\partial e_l^*}{\partial \theta_j} \tag{25}$$

$$\frac{dx_i^*}{d\theta_i} = \frac{\partial x_i^*}{\partial \theta_i} + \sum_j \frac{\partial x_i^*}{\partial e_j^*} \cdot \frac{\partial e_j^*}{\partial \theta_i}; \quad \frac{dx_i^*}{d\theta_j} = \frac{\partial x_i^*}{\partial \theta_j} + \sum_l \frac{\partial x_i^*}{\partial e_l^*} \cdot \frac{\partial e_l^*}{\partial \theta_j} \tag{26}$$

Table 2: Computations of derivatives

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

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

A. Impact on the emergence of cooperation

Impact of net price, p

Impact of p_i

We first analyze the impact of p_i on concessionaire i's willingness to cooperate, and we obtain:

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

The second term between brackets is positive as $\frac{\partial e_i^*}{\partial p_i} < 0$, $1 - \delta D_{ii} g_{e_i^*} > 0$ and $\frac{\partial e_j^*}{\partial p_i} > 0$. Thus $\frac{d\left(\Pi_i^c - \Pi_i^d\right)}{dp_i} > 0$ if the condition on concessionaire i's *willingness-to-cooperate* is satisfied. So, an increase in p_i results in a larger value of $\frac{d\left(\Pi_i^c - \Pi_i^d\right)}{dp_i}$, thus an increase in the *willingness-to-cooperate*.

Effect of p_j, $j \neq i$

In this case we have

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

First, if both dispersal rates D_{ij} and D_{ji} are small, then the first and second term between brackets on the RHS of the equality are small, which implies that $\frac{d\left(\Pi_i^c - \Pi_i^d\right)}{dp_j}$ is positive. Indeed, when D_{ij} and D_{ji} are small, then $\frac{\partial e_i^*}{\partial p_j}$ and $\frac{\partial e_j^*}{\partial p_j} D_{ji} g_{e_j^*}$ are small. And the sign of the term between brackets (and thus of $\frac{d\left(\Pi_i^c - \Pi_i^d\right)}{dp_j}$) is similar to the sign of $\sum_{l\neq i,j}\frac{\partial e_l^*}{\partial p_j} D_{li} g_{e_l^*}$, which is positive. Second, if $D_{ii} + D_{ij}$ and $D_{jj} + D_{ji}$ are large, then $\sum_{l\neq i,j}\frac{\partial e_l^*}{\partial p_j} D_{li} g_{e_l^*}$ is small, which implies that $\frac{d\left(\Pi_i^c - \Pi_i^d\right)}{dp_j}$ is negative.

Impact of growth, α

Effect of α_i

We have $\frac{d\left(\Pi_i^c - \Pi_i^d\right)}{d\alpha_i} = \frac{\delta^{kT} p_i}{1-\delta}\left[\frac{\partial e_i^*}{\partial \alpha_i}\left(\delta D_{ii} g_{e_i^*} - 1\right) + \delta D_{ii}\left(g_{\alpha_i^*} - (1-\delta^{T-1}) g_{\bar{\alpha}_i}\right)\right]$ so, if D_{ii} is small while $\bar{e}_i > 0$, then $\frac{d\left(\Pi_i^c - \Pi_i^d\right)}{d\alpha_i} < 0$ holds. If $D_{ii} = 1$, then $1 - \delta D_{ii} g_{e_i^*} = 0$ and $\frac{d\left(\Pi_i^c - \Pi_i^d\right)}{d\alpha_i} > 0$ since $g_{\alpha_i^*} - (1-\delta^{T-1}) g_{\bar{\alpha}_i} > 0$. By a continuity argument, this conclusion remains valid when D_{ii} is large.

Effect of α_j, $j \neq i$

We have $\frac{d\left(\Pi_i^c - \Pi_i^d\right)}{d\alpha_j} = \frac{\delta^{(k+1)T} p_i}{1-\delta} D_{ji} \left(g_{\alpha_j^*} + g_{e_j^*} \right) > 0$.

Impact of dispersal rate, D

Effect of D_{ii}

We have $\frac{d\left(\Pi_i^c - \Pi_i^d\right)}{dD_{ii}} = \frac{\delta^{kT} p_i}{1-\delta} \left(\delta[g(e_i^*, \alpha_i) - g(\bar{e}_i, \alpha_i)] + \delta^T g(\bar{e}_i, \alpha_i) - \left(1 - \delta D_{ii} g_{e_i^*}\right) \frac{\partial e_i^*}{\partial D_{ii}} \right)$. The RHS term is the sum of two terms of opposite signs, and is thus ambiguous.

Effect of D_{ij}

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

Effect of D_{ji}

We have $\frac{d\left(\Pi_i^c - \Pi_i^d\right)}{dD_{ji}} = \frac{\delta^{(k+1)T} p_i}{1-\delta} \left[\frac{\partial e_j^*}{\partial D_{ji}} D_{ji} g_{e_j^*} + g(e_j^*, \alpha_j) \right] > 0$.

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

We have $\frac{d\bar{T}_i}{d\theta} = \frac{1}{\ln(\delta)\left[\delta(\bar{x}_i - x_i^*) + e_i^* - \bar{e}_i\right]} \left[\frac{\partial e_i^*}{\partial \theta} - \delta \frac{dx_i^*}{d\theta} + \left(\frac{\delta x_i^* - e_i^*}{\delta \bar{x}_i - \bar{e}_i} \right) \left(\delta \frac{d\bar{x}_i}{d\theta} - \frac{\partial \bar{e}_i}{\partial \theta} \right) \right]$. Since $\delta \in (0,1)$ and $\delta(\bar{x}_i - x_i^*) + e_i^* - \bar{e}_i > 0$, the first term in this equality is always negative. Using (25)-(26) and Table 1, we have $\delta \frac{d\bar{x}_i}{d\theta} - \frac{\partial \bar{e}_i}{\partial \theta} \gtrless 0$. Notice that:

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

and $\frac{d\bar{T}_i}{d\theta} > 0$ for $\theta = \{p_i; \alpha_j; D_{ji}\}$ ($\frac{d\bar{T}_i}{dD_{ij}} < 0$). The sign is ambiguous for $\theta = \{p_j; \alpha_i; D_{ii}\}$.

Effect of p_j, $j \neq i$

$$\frac{\partial e_i^*}{\partial p_j} \left(1 - \delta \frac{\partial x_i^*}{\partial e_i^*}\right) - \delta \sum_{l \neq i} \frac{\partial x_i^*}{\partial e_l^*} \frac{\partial e_l^*}{\partial p_j} + \delta \left(\frac{\delta x_i^* - e_i^*}{\delta \bar{x}_i - \bar{e}_i} \right) \sum_{l \neq i} \frac{\partial \bar{x}_i}{\partial e_l^*} \frac{\partial e_l^*}{\partial p_j} \tag{27}$$

$$\Leftrightarrow \frac{\partial e_i^*}{\partial p_j}(1 - \delta D_{ii} g_{e_i}) + \delta \left(\frac{\delta(x_i^* - \bar{x}_i) - e_i^* + \bar{e}_i}{\delta \bar{x}_i - \bar{e}_i} \right) \left(D_{ji} g_{e_j} \frac{\partial e_j^*}{\partial p_j} + \sum_{l \neq i,j} D_{li} g_{e_l} \frac{\partial e_l^*}{\partial p_j} \right) \tag{28}$$

If D_{ij} is small enough, then (36) is negative, and $\bar{T}_i$ 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: $\bar{T}_i$ decreases when p_j increases.

Indeed, this leads to a small value of the last term between brackets. Thus, the sign of $\frac{d\bar{T}_i}{dp_j}$ depends only on that of $\frac{\partial e_i^*}{\partial p_j}(1-\delta D_{ii}g_{e_i})$, which is positive. We thus conclude that $\frac{\partial \bar{T}_i}{\partial p_j}$ is negative.

Effect of α_i

$$\frac{\partial e_i^*}{\partial \alpha_i}\left(1-\delta\frac{\partial x_i^*}{\partial e_i^*}\right)-\delta\frac{\partial x_i^*}{\partial \alpha_i}+\left(\frac{\delta x_i^*-e_i^*}{\delta \bar{x}_i-\bar{e}_i}\right)\left[\delta\left(\frac{\partial \bar{x}_i}{\partial \alpha_i}+\frac{\partial \bar{x}_i}{\partial \bar{e}_i}\frac{\partial \bar{e}_i}{\partial \alpha_i}\right)-\frac{\partial \bar{e}_i}{\partial \alpha_i}\right] \tag{29}$$

$$\Leftrightarrow \frac{\partial e_i^*}{\partial \alpha_i}\left(1-\delta D_{ii}g_{e_i^*}\right)-\delta D_{ii}\left[g_{\alpha_i^*}-g_{\bar{\alpha}_i}\left(\frac{\delta x_i^*-e_i^*}{\delta \bar{x}_i-\bar{e}_i}\right)\right] \tag{30}$$

If δD_{ii} is small enough while $\bar{e}_i$ remains positive, then $\bar{T}_i$ decreases as α_i increases.

Effect of D_{ii}

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

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

If δ is small enough while $\bar{e}_i > 0$ then the sign of the expression is that of $\frac{\partial e_i^*}{\partial D_{ii}}$, which is positive.