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Unitization of Spatially Connected Renewable Resources

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Daniel T. Kaffine and Christopher Costello

Abstract

Spatial connectivity of renewable resources induces a spatial externality in extraction. We explore the consequences of decentralized spatial property rights in the presence of spatial externalities. We generalize the notion of unitization—developed to enhance cooperative extraction of oil and gas fields—and apply it to renewable resources which face a similar spatial commons problem. We find that unitizing a common pool renewable resource can yield first-best outcomes even when participation is voluntary, provided profit sharing rules can vary by participant.

KEYWORDS: fisheries, property rights, spatial bioeconomics, unitization

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1 Introduction

This paper concerns coordination among property owners who exploit a spatially connected renewable resource. A salient example is the fishery where fish movement across space induces a spatial externality in extraction. The collapse of many of the world's fisheries (Worm et al., 2006, Myers and Worm, 2003, Jackson et al., 2001) has led to the search for policy approaches to prevent further collapse and, perhaps, recover depleted stocks (Worm et al., 2009). The failure of traditional regulation structures to halt this collapse has led economists to propose various property-rights based approaches including Individual Tradeable Quotas (ITQs), which allocate units of harvest, and Territorial User Rights Fisheries (TURFs), which allocate units of space to private firms, cooperatives, or fishermen.[1] Economists argue that appropriate assignment of rights internalizes externalities and facilitates stewardship, leading to sustainability through a profit motive.[2] In the United States, there is growing policy interest in ocean zoning and marine spatial planning, further motivating our inquiry. Yet for spatially connected resources, the spatial commons problem may persist, even when spatial property rights (TURFs) are assigned, monitored, enforced, and perpetual (Janmaat, 2005). This is because harvest in one TURF inherently affects production, profitability, and therefore incentives in other TURFs. We examine this market failure in detail and analyze one solution grounded both in economic theory and in historical use.

While compelling, the problem of spatial externalities in a common pool is not new. Multiple owners of mineral rights to an oil or gas field, where adjacent owners have an incentive to over-invest in capital and extract at too rapid a rate, has similar (though not identical) characteristics. A well-known solution in that context is unitization, where landowners are contractually

[1] For example, the 2007 reauthorization of the Magnuson-Stevens Fishery Conservation and Management Act allows for various tradeable property schemes. A recent study (Costello et al., 2008) suggests that ITQs have been successful in slowing fishery collapse.

[2] See Hannesson (2004) for an excellent discussion of attempts to privatize the ocean with ITQs and spatial rights. Examples of formalized spatial property right systems include TURFs in Chile (Cancino et al., 2007), community cooperatives in Japan and Mexico, and the 200 mile Exclusive Economic Zones (EEZs) established by the Law of the Sea; a famous informal example occurs in the Maine lobster fishery where harbor 'gangs' exercise de facto spatial rights (Acheson, 1988).

obligated to pool profits to minimize redundant drilling and extraction effort.[3] We generalize the concept of unitization as a possible solution to the spatial renewable resource problem. The idea is that by sharing profits, each owner has an interest in the profits of other owners, and is thus less likely to over-harvest her own patch for personal gain if it would harm her neighbor. The conditions under which this system works to solve the commons problem is amenable to bioeconomic analysis.

We stress that this is not simply a theoretical exercise, as there are several examples of such institutions that have arisen organically from historical communal use of spatially connected renewable resources.[4] For example, the sakuraebi (a small pink shrimp) fishery of Japan is an example of a profit-sharing system across TURFs that was introduced to alleviate inefficiencies associated with decentralized harvest by three separate TURFs within Suruga Bay. While the introduction of the TURF system had promoted rationalization within each of the three TURFs, stock dispersal and heterogeneity had led to stringent competition between TURFs; this competition went so far as to include on and off-shore violence (Uchida and Wilen, 2004). Ten years of this destructive behavior led the shrimp fishermen to form the Sakuraebi Harvesters' Association (SHA) to coordinate harvest between the individual TURFs. The SHA manages fishing activity on a daily basis, and as a result, only half the fleet will be engaged in fishing on any given day. From the landed sales, a percentage fee is collected by the SHA, with the remaining revenue net

[3] The problem of unitization and contracting between users of a nonrenewable common pool resource has been studied in depth for the oil industry in a series of papers by Libecap and Wiggins (Libecap and Wiggins, 1984, Wiggins and Libecap, 1985, Libecap and Wiggins, 1985). They examine the contracting success, and frequently the failure, of private firms drilling the same common oil field. They generally find that heterogeneity plays a key role in thwarting the success of contracts to lessen rent dissipation and overproduction.

[4] For example, profits are pooled among cooperative members within the walleye pollack fishery of the Nishi region of Japan and redistributed to TURF members (Uchida and Watanobe, 2008). The loco fisheries in Chile's TURF system also use partial revenue pooling mechanisms within a TURF to mitigate race-to-fish incentives (Uchida and Wilen, 2005). Within the deep sea crab fishery of New Zealand, quota owners have "invested" their quota shares within Crabco, the sole company involved in the crab fishing operation. Profits are returned to investors based on the share invested in the company (Mincher, 2008).

of fixed costs divided among boat captains and crew members (Uchida and Baba, 2008).

Another spatial fishery of note is the fishing cooperatives of Baja California, Mexico, a collection of small community-based cooperative fisheries that primarily target spiny lobster and abalone. Several of these fisheries in the Vizcaino Peninsula region have formed a federation (Fedecoop) to coordinate harvest across the spatial fisheries. Each of the 9 members of Fedecoop contribute a share of profits to the federation, which in turn provides benefits for the individual cooperatives. While not a spatially defined fishery, the Chignik salmon fishery of Alaska featured a short-lived cooperative whereby roughly 20% of license holders participated in fishing, while the remaining members were idle. Revenues where then returned to cooperative members based on a pre-determined formula, such that fishing members received \$63,000 and non-fishing members received \$23,000 (Costello and Deacon, 2007).[5]

While sharing institutions have emerged in ad hoc examples, no comprehensive theory exists to help guide the design of these institutions across spatial property rights owners. For example, can first-best efficient harvest be achieved with unitization? How does the structure of profit sharing affect the achievement of first-best outcomes? How would design depend on the biological or economic characteristics of the resource? Is contractual obligation required? Or can the unitization scheme be designed to incentivize participation? Addressing this set of questions about spatially connected renewable resource owners will require a new model that leverages insights from spatial bioeconomics, international fisheries management, and common pool resource games.

Our treatment incorporates a general framework of harvest decisions where a number of owners make decentralized decisions regarding spatially explicit resource use. The general renewable resource model we consider is both dynamic and spatial; resources grow and disperse. Spatial connectivity among resource "patches" (e.g. fish/larval movement) creates a spatial externality.[6] Unsurprisingly, in the absence of coordination, patch owners will tend to overexploit the resident stock.[7] Thus, any discussion of harvest

[5] The cooperative was disbanded by a court ruling that held that the cooperative was illegal on the grounds that it was illegal for a fisherman to profit from a right to fish without undertaking any actual fishing activity.

[6] This feature is present at some life-history stage for many commercially viable species.

[7] Clearly, increasing patch size could alleviate this problem (White and Costello, 2010). While we assume here that patch geography is given exogenously, a similar model could be used to optimize property rights delineation.

inefficiency will have to consider both dynamic and spatial externalities, in addition to strategic behavior between patch owners.

The dynamic aspect of the model is in the spirit of existing dynamic optimization models (Clark, 1990), while the spatial aspects build on existing models of "patchy" bioeconomics, e.g. Brown and Roughgarden (1997) Sanchirico and Wilen (1999), Sanchirico and Wilen (2001), Sanchirico and Wilen (2002) Sanchirico and Wilen (2005) and Costello and Polasky (2008). That literature focuses on fishery management under open access, regulated open access, or the sole owner. Our paper examines the equilibrium behavior of decentralized spatially connected patch owners.

We also build on a rich literature that considers the joint exploitation of a single resource stock by several countries, beginning with the seminal works of Munro (1979) and Levhari and Mirman (1980). This "fish wars" literature identified a persistent externality of one country on another where the resource stock moved across international jurisdictions, a phenomenon that has recently been corroborated empirically (McWhinnie, 2009). A substantial body of literature utilizes game theoretic analysis to consider the sharing of surpluses generated by binding or non-binding cooperative agreements with side payments (Bjorndal and Munro, 2004, Kaitala and Pohjola, 1988). Recent literature has considered the success and stability of coalitions consisting of multiple fishing states, such as regional fisheries management organizations or RFMOs (Pintassilgo and Lindroos, 2008, Pintassilgo et al., 2010). A key consideration in this recent literature is the challenge of new member entry into the RFMO; by contrast, the system under consideration here consists of a fixed number of patch owners with secure property rights. Thus, while many of the insights of that literature also apply here, we extend the bioeconomic model to allow for resource production and dispersal in an arbitrarily large and arbitrarily connected set of jurisdictions (i.e. a "metapopulation") and explore the ability of unitization to correct the ensuing externality across these spatial property rights owners.

We focus here on examples of profit sharing *across* spatial units of ownership, as opposed to profit sharing *within* spatially defined units of ownership. Within a spatially-defined unit of ownership (i.e. a TURF), profit-sharing can be used to induce cooperation between multiple harvesters. This possibility has been explored theoretically (Heintzelman et al., 2009, Gaspart and Seki, 2003), experimentally (Schott et al., 2007), and empirically (Uchida and Wilen, 2004, Uchida and Baba, 2008).

By exploiting the special structure of our dynamic and spatial game we are able to obtain sharp analytical results of an otherwise intractable problem. Our benchmark case accords with the results of Janmaat (2005) who finds that for spatially connected renewable resources, spatial property rights alone do not yield efficient outcomes, except in trivial cases. We then consider coordination between patch owners via a generalization of unitization. Under unitization, each member contributes a share of her profit to a general pool that is ultimately redistributed across members in a particular way. The details of the levels of contribution and redistribution affect both efficiency and participation; this is the focus of much of our analysis.

If properly designed, unitization acts to mitigate the commons problem. Thus the individual patch owner's decisions appear more like those of the sole owner. We find that under contractually mandatory participation, unitization can yield first-best outcomes, but only when all profits are pooled. We show that allowing for endogenous participation in the unitization scheme can still yield first-best outcomes, provided that shares can vary across participants. We proceed by developing an analytical model of spatially-connected renewable resources and deriving results regarding the ability of a well-engineered unitization scheme to achieve efficiency in resource use when participation is mandatory, and when it is voluntary.

2 A model of spatial property rights for renewable resources

We require a spatially explicit dynamic bioeconomic model that is analytically tractable yet allows for spatial heterogeneity in economics, biology, and the environment. We build upon the dynamic model structure in Costello and Polasky (2008). Each of N resource patches, indexed $i = 1, 2, ..., N$, is exclusively managed by a single owner who chooses harvest in her own patch in discrete time periods, $t = 0, 1, 2, ...$ Tenure is assumed to be guaranteed and infinite.[8] While our theory applies to any spatially connected renewable resource, it facilitates exposition to focus on the fishery as an example.

2.1 Growth and spatial connectivity

Stock at the beginning of time t in patch i is given by x_{it}. Harvest in each patch i is a decision variable at each time t and is given by h_{it}, and escapement e_{it} is defined as $e_{it} = x_{it} - h_{it}$. Patches are spatially interconnected, e.g. by migrating fish or larvae dispersing via ocean currents. The timing is thus:

[8] See Costello and Kaffine (2008) for a discussion of how uncertain tenure affects harvest incentives for renewable resources.

the present period stock (x_{it}) is observed and then harvested (h_{it}) resulting in escapement (e_{it}). This escapement produces young who disperse according to the following equation of motion:

$$x_{it+1} = \sum_{j}^{N} f_j(e_{jt}) D_{ji}, \qquad (1)$$

where $f_j(e_{jt})$ is a patch specific growth function that reflects idiosyncracies of patch ecology (e.g. habitat quality) and D_{ji} is the fraction of resident stock that disperses from patch j to patch i each period, $D_{ji} \geq 0$, $\sum_i^N D_{ji} = 1$, where $D_{jj} \leq 1$ reflects self-retention (Mitarai et al., 2009).[9] The initial stock in patch i is x_{i0}. The function $f_i(e)$ is assumed to have the standard properties for all i: $f_i'(e) > 0$, $f_i''(e) < 0$, and $f_i(0) = 0$.

2.2 Economic returns

In addition to patch-specific heterogeneity in production and dispersal, we allow for differential economic returns. We assume that the resource-extracting system under consideration is small relative to the total market, implying perfectly elastic demand.[10] The current period profit from harvesting h_{it} from patch i at time t is given by the harvest model:

$$\Pi_{it} = (p_i - c_i) h_{it} \qquad (2)$$

$$= b_i(x_{it} - e_{it}), \qquad (3)$$

where p_i and c_i are patch-specific prices and marginal harvest costs, we define as marginal profit $b_i \equiv p_i - c_i$, and make use of the identity $h_{it} \equiv x_{it} - e_{it}$.[11] Prices may vary across patches due to spatial heterogeneity in the resource quality (e.g. sea urchin roe quality depends on habitat which is patch specific). Differences in costs may reflect differences in patch-specific difficulty of harvest (e.g. due to depth or wind). By assuming $b_i > 0 \ \forall i$, we ensure that some harvest would always be (at least myopically) profitable in every patch. Before considering the problem faced by decentralized patch owners under unitization,

[9] The parameter D_{ji} captures larval dispersal across space and will be species-specific.

[10] This also implies that changes in social welfare are entirely captured by changes in producer profits.

[11] We leave the exploration of decentralized spatial bioeconomic models with stock effects to future work.

the next section derives two key results for comparison: the sole owner solution and the uncoordinated, decentralized solution.

3 Benchmark results

3.1 The sole owner

Consider the benchmark case where a sole owner simultaneously manages all N interconnected resource patches. Even for a sole owner, this poses a formidable challenge as it generalizes the standard renewable resource harvesting problem to account for spatial interconnections (via D_{ji}) among an arbitrarily large collection of patches. By imposing a modest amount of structure on this problem, we will be able to derive closed form analytical results. We thus restrict attention to interior solutions where some harvest occurs in each patch. While corner solutions (where some patches are optimally left unharvested or are harvested to extinction) are a theoretical possibility (see Costello and Polasky (2008)), we assume that conditions are such that some positive but non-extinguishing harvest is optimal: $x_{it} > h_{it} > 0\ \forall i, t$. We also adopt a benign assumption about dispersal:

Assumption 1. *There is some out-of-patch dispersal:* $D_{ii} < 1$, $\forall i$.

This assumption simply requires that patches are in fact spatially-connected. A violation of this assumption (so $D_{ii} = 1$) trivializes the problem by eliminating spatial connectivity, whereby the sole owner solves a series of N unconnected standard renewable resource harvesting problems.

The sole owner's objective is to choose the patch-specific escapement vector to maximize the discounted net present value of profit (Equation 2) across all patches and all time. Letting $\mathbf{x_t}$ denote the vector $[x_{1t}...x_{Nt}]$ and $\mathbf{e_t} = [e_{1t}...e_{Nt}]$, the sole owner's dynamic programming equation is:

$$V_t(\mathbf{x_t}) = \max_{\mathbf{e_t}} \sum_{i=1}^{N} b_i(x_{it} - e_{it}) + \delta V_{t+1}(\mathbf{x_{t+1}}), \tag{4}$$

which is subject to the biological constraints (Equation 1), and a discount factor $\delta \leq 1$.

Differentiating with respect to escapement gives the following necessary condition for an interior solution:

$$-b_i + \delta \sum_{j=1}^{N} \frac{\partial V_{t+1}(\mathbf{x_{t+1}})}{\partial x_{jt+1}} \frac{\partial x_{jt+1}}{\partial e_{it}} = 0 \quad \forall i, \tag{5}$$

where the first term captures the marginal cost of increasing escapement (and thus decreasing harvest) in the current period, and the second captures the marginal benefit in future payoffs to all patches from that increase in escapement. Because all patches are owned by the same harvester, spillovers from dispersal from each patch are fully internalized.

By using escapement ($\mathbf{e_t}$) (rather than harvest) as the control variable, this complicated dynamic optimization problem has a special structure, called "state independent control," for which the first-order conditions are independent of stock, x_{it} (Costello and Polasky, 2008).[12] This allows us to separate the problem temporally, and implies that escapement is location-specific, but time-independent (consistent with Proposition 1 in Costello and Polasky (2008)). This result accords with, but extends, existing resource models with perfectly elastic demand for which a bang-bang solution is implemented to achieve an optimal escapement. Because optimal escapement in patch i is constant, additional units of stock are simply harvested, so the shadow value on stock is just its net price: $\frac{\partial V_{t+1}(\mathbf{x_{t+1}})}{\partial x_{jt+1}} = b_j \; \forall j$. The final term, $\frac{\partial x_{jt+1}}{\partial e_{it}}$ equals $f_i'(e_{it})D_{ij}$ by rewriting Equation 1 in terms of x_{jt+1} and differentiating with respect to e_{it}. Thus, what would otherwise be an extremely complicated spatial temporal optimization problem has a first order condition that compactly reduces to:

$$-b_i + \delta \sum_{j=1}^{N} b_j f_i'(e_{it}^{\mathcal{SO}}) D_{ij} = 0 \quad \forall i. \tag{6}$$

The optimal level of escapement under a sole owner $e_{it}^{\mathcal{SO}}$ will trade off the present benefit of harvest against the sum of future growth and dispersal to all patches, yielding a spatially modified golden rule for spatially-connected renewable resources:

$$f_i'(e_{it}^{\mathcal{SO}}) = \frac{b_i}{\delta \sum_{j=1}^{N} b_j D_{ij}} \quad \forall i. \tag{7}$$

By the concavity of $f_i(e_i)$, $e_{it}^{\mathcal{SO}}$ is thus decreasing in own price, b_i, and increasing in the discount factor, δ. Note that in the absence of space, Equation

[12] If harvest was the control, then to achieve a desired escapement would require a state-dependent control by the identity $e_{it} \equiv x_{it} - h_{it}$.

7 collapses to the familiar golden rule of resource economics: $f'(e) = 1/\delta$. While Equation 7 provides a useful benchmark, the remainder of this paper is devoted to the case of decentralized ownership of these resource patches.

3.2 Uncoordinated spatial ownership

The other benchmark case we will utilize is uncoordinated, decentralized ownership of the N patches. When coordination is absent, each of the N patch owners maximizes her patch-specific returns, taking as given the behavior of connected patch owners. The dynamic programming equation for owner i is:

$$V_{it}(\mathbf{x_t}) = \max_{e_{it}} b_i(x_{it} - e_{it}) + \delta V_{it+1}(\mathbf{x_{t+1}}). \tag{8}$$

Owner i's choice must now account for the effect of all other patch owners' decisions on her value function. The necessary condition for owner i is:

$$-b_i + \delta \left[\frac{\partial V_{it+1}(\mathbf{x_{t+1}})}{\partial x_{1t+1}} \frac{\partial x_{1t+1}}{\partial e_{it}} + ... + \frac{\partial V_{it+1}(\mathbf{x_{t+1}})}{\partial x_{Nt+1}} \frac{\partial x_{Nt+1}}{\partial e_{it}} \right] = 0, \text{or} \tag{9}$$

$$-b_i + \delta \sum_{j=1}^{N} \frac{\partial V_{it+1}(\mathbf{x_{t+1}})}{\partial x_{jt+1}} \frac{\partial x_{jt+1}}{\partial e_{it}} = 0. \tag{10}$$

We assume that all model parameters, contemporaneous escapements, and contemporaneous stocks are common knowledge to all patch owners. We consider a dynamic Cournot-Nash model in which owners simultaneously choose escapements in period t knowing that this procedure will be repeated every year into the future. Following the classic paper by Levhari and Mirman (1980),[13] we solve for the subgame perfect Nash equilibrium by analytical backward induction on the Bellman equation for each owner i (see Appendix for proof of Lemma 1 which contains details). Of principal significance here are our findings that under the assumptions of this model (1) patch owner i's best response in period t is independent of period t choices by other patch owners and (2) patch owner i's optimal choice of escapement in period $t + 1$

[13] To our knowledge, the first application of the dynamic Cournot-Nash model to renewable natural resources.

is independent of choices made by *any* owner prior to period t.[14] Together, these results imply that the best response function of owner i reduces to:

$$-b_i + \delta b_i f_i'(e_{it}) D_{ii} = 0. \tag{11}$$

This yields the following result:

Lemma 1. *Equilibrium escapement for uncoordinated spatial owners in the above problem are given (in every period but the final period) by:*

$$f_i'(e_{it}^{\mathcal{UC}}) = \frac{1}{\delta D_{ii}} \tag{12}$$

Proof. See Appendix □

Because owner i's best response is independent of e_{jt} $(j \neq i)$, the escapements given in Lemma 1 define a unique subgame perfect Nash equilibrium vector of escapements for each owner under decentralized ownership. This result leads to the following first proposition regarding the efficiency of spatial property rights in the absence of coordination.

Proposition 1. *Under Assumption 1, $e_{it}^{\mathcal{UC}} < e_{it}^{\mathcal{SO}}$.*

Proof. By Equation 7 and Lemma 1 we have $f_i'(e_{it}^{\mathcal{SO}}) = \frac{1}{\delta D_{ii} + \delta \sum_{j \neq i}^{N} (b_j/b_i) D_{ij}} < \frac{1}{\delta D_{ii}} = f_i'(e_{it}^{\mathcal{UC}})$. Because $f_i'(e) > 0$ and $f_i''(e) < 0$, $e_{it}^{\mathcal{UC}} < e_{it}^{\mathcal{SO}}$. □

The magnitude of the difference between the sole owner and uncoordinated equilibria will depend on the extent of the spatial externality, captured by the out-dispersal term in the denominator $\delta \sum_{j \neq i}^{N} (b_j/b_i) D_{ij}$. The larger is this term, the larger is the wedge between the sole owner's escapement in that patch and that which is chosen by the uncoordinated owner.[15] To the extent that uncoordinated harvest is inefficiently excessive (see Proposition

[14] Thus the open loop and feedback control rules are identical. This result was established, and coined *state separability* for continuous time models by Dockner et al. (1985). Identifying this result is made possible because we use escapement (rather than harvest) as the control.

[15] We make a few notes about Proposition 1 when Assumption 1 does not hold. If $f_i'(0) \leq \frac{1}{\delta D_{ii}}$, the optimal escapement is $e_{it}^{\mathcal{UC}} = 0$ by the non-negativity constraint on e_{it}. On the other hand, if $D_{ij} = 0$ for $i \neq j$, the optimal escapement is equivalent to the economically efficient sole owner's. Without dispersal, each owner controls a self-contained fiefdom and property rights

1), coordination will be required to align incentives across spatial rights holders. While it is true that uncoordinated spatial property rights may fail to completely solve the commons problem, it is likely that the owners themselves would also recognize this fact, and take steps to coordinate. We address this topic below, beginning with a simple, yet powerful coordinating mechanism.

4 Unitization

We have shown that even with well defined and enforced spatial property rights, uncoordinated owners will typically not achieve economically efficient resource use (Proposition 1). Coordination may be induced by a Coasian bargaining solution or by other mechanisms requiring side payments between users. Real world examples of spatial property rights in renewable resources may involve hundreds of interconnected patches, and thus the number of side payments would quickly become large ($\frac{N(N-1)}{2}$).[16] We thus focus on unitization as a simple budget balanced, fully internal mechanism with no required side payments.

4.1 Unitization scheme

Consider a unitization scheme where each owner makes a *contribution* $0 \leq \alpha_i \leq 1$ of her profits to a pool.[17] *Dividend* $0 < \gamma_i < 1$ of this aggregate pool is then redistributed to patch i, such that $\sum_i^N \gamma_i = 1$.[18] A particular unitization scheme is defined by $\{\boldsymbol{\alpha}, \boldsymbol{\gamma}\}$, where $\boldsymbol{\alpha} = [\alpha_1, \alpha_2, ..., \alpha_N]$ and $\boldsymbol{\gamma} = [\gamma_1, \gamma_2, ..., \gamma_N]$.

can be assigned confidently without concern for coordination or cooperation; efficient harvest will occur for owners solely interested in their own profits. However, as noted in the introduction, larval dispersal in fisheries is typically larger than practical spatial property right assignments to individual users.

[16] A small example is in Baja California where the 9 spatial property rights owners in the cooperative "Fedecoop" would require 36 separate annual side payments. A large example is in Chile where 453 permanent TURFs exist for harvesting an abalone-like snail, which could require $> 100,000$ side payments.

[17] Consistent with our assumption that profits (rather than, e.g., revenues) are shared, Libecap and Smith (1999) argue that production and cost shares must coincide to induce efficiency in unitization contracts for oil and gas extraction.

[18] In practice, the redistribution may not be entirely pecuniary. For example, in Chile and Japan profit sharing partly pays for science, monitoring, and enforcement. For oil and gas, coordination is undertaken by a "unit operator"

For the first part of our analysis, we adopt the following assumption regarding participation in unitization:

Assumption 2. *All N owners are contractually obligated to participate in the unitization scheme, $\{\boldsymbol{\alpha}, \boldsymbol{\gamma}\}$.*

Under Assumption 2, patch owners are legally bound to participate in the unitization scheme, as is typically the case for mineral rights owners in unitized oil and gas fields (we later relax this assumption). If $\alpha_i = 0\ \forall i$, no profit sharing occurs, and thus the resource is not unitized and owners are uncoordinated. If $\alpha_i = 1\ \forall i$, then all profits are shared (as is the case for unitized oil and gas fields); subsequent redistribution to each owner is governed by $\boldsymbol{\gamma}$. For any $\{\boldsymbol{\alpha}, \boldsymbol{\gamma}\}$, each individual owner chooses escapement taking other owners' decisions as given.

The dynamic programming equation for patch owner i is given by:

$$V_{it}(\mathbf{x_t}) = \max_{e_{it}} (1-\alpha_i) b_i (x_{it} - e_{it}) + \gamma_i \sum_{j=1}^{N} \alpha_j b_j (x_{jt} - e_{jt}) + \delta V_{it+1}(\mathbf{x_{t+1}}) \quad (13)$$

with necessary condition:

$$-(1-\alpha_i) b_i - \alpha_i \gamma_i b_i + \delta \sum_{j=1}^{N} \frac{\partial V_{it+1}(\mathbf{x_{t+1}})}{\partial x_{jt+1}} \frac{\partial x_{jt+1}}{\partial e_{it}} = 0. \quad (14)$$

Because owner i takes all e_{jt} $(j \neq i)$ as given, from the perspective of owner i, owner j immediately harvests any additional stock down to the given escapement level yielding marginal value, b_j.[19] That value accrues to owner i based on the dividend, and we obtain: $\frac{\partial V_{it+1}(\mathbf{x_{t+1}})}{\partial x_{jt+1}} = \gamma_i b_j\ \forall i, j$. Combining this along with differentiation of Equation 1 gives owner i's best response function:

$$-(1-\alpha_i) b_i - \alpha_i \gamma_i b_i + \delta \left((1-\alpha_i) b_i f_i'(e_{it}) D_{ii} + \gamma_i \sum_{j=1}^{N} \alpha_j b_j f_i'(e_{it}) D_{ij} \right) = 0, \quad (15)$$

a concept that has been adopted (in principle, not in name) in some fisheries, e.g. the Chignik Salmon Cooperative (Deacon et al., 2008).

[19] This result can be shown using backward induction and the Bellman equation, exactly parallel to the proof of Lemma 1.

which remains independent of any other owner's escapement decision. The left hand terms represents the current period marginal cost of increasing escapement: $(1-\alpha_i)$ forgone private harvest value, and $\alpha_i\gamma_i$ share of the forgone harvest value. The right term represents the marginal benefit: discounted private $(1-\alpha_i)$ and pooled (γ_i) share of future contributed value of marginal growth and dispersal of the resource.

Thus, we can immediately write the resulting optimal escapement rule $e_{it}^{\{\boldsymbol{\alpha},\boldsymbol{\gamma}\}}$ as a function of the unitization scheme $\{\boldsymbol{\alpha},\boldsymbol{\gamma}\}$as follows:

$$f_i'(e_{it}^{\{\boldsymbol{\alpha},\boldsymbol{\gamma}\}}) = \frac{(1-\alpha_i)b_i + \alpha_i\gamma_i b_i}{\delta((1-\alpha_i)b_i D_{ii} + \gamma_i \sum_{j=1}^{N} \alpha_j b_j D_{ij})}. \tag{16}$$

Equation 16 defines a unique subgame perfect Nash equilibrium vector of escapements for each owner under unitization scheme $\{\boldsymbol{\alpha},\boldsymbol{\gamma}\}$.[20] Intuitively, if $\alpha_i = 0, \forall i$ and no profits are shared, escapement should be identical to the case of uncoordinated patch owners, $e_i^{\mathcal{UC}}$. Setting $\alpha_i = 0$ in equation 16 confirms this intuition.

How efficient is full unitization ($\alpha_i = 1$, $\forall i$)? Intuitively, full unitization should generate incentives for all patch owners to internalize their effect on other patch's profits. Let $e_i^{\mathcal{F}}$ be the escapement chosen by each owner under full unitization. The following proposition shows that this escapement level will be equivalent to the first-best.

Proposition 2. *Under Assumptions 1-2, the subgame perfect Nash equilibrium escapement under full unitization ($\alpha_i = 1\ \forall i$) is identical to the economically efficient sole owner's escapement, $e_i^{\mathcal{F}} = e_i^{\mathcal{SO}}$, $\forall i$.*

Proof. Setting $\alpha_i = 1$ in Equation 16 yields the following escapement rule under full unitization:

$$f_i'(e_i^{\mathcal{F}}) = \frac{b_i}{\delta \sum_{j=1}^{N} b_j D_{ij}}. \tag{17}$$

The result follows by inspection of Equations 17 and 7. □

This intuitive yet powerful result seems to solve our efficiency problem: simply constraining all users to fully share profits yields economic efficiency.

[20] Note that equilibrium profile of escapements under the three cases we consider (sole owner, uncoordinated owners, and unitization) are all independent of the state, and are thus constant over time. We henceforth suppress time subscripts for ease of exposition.

Under full unitization, each owner chooses the escapement in her patch that maximizes the joint return of all patches, which is precisely the decision that a sole owner would make.[21] This derivation yields an additional useful result:

Corollary 1. *Under Assumptions 1 - 2 and full unitization ($\alpha_i = 1\ \forall i$), escapement and efficiency are independent of the dividend $\gamma_i\ \forall i$.*

Proof. This result follows from the fact that Equation 17 is independent of γ_i. □

4.2 Partial unitization

We have shown that when $\alpha_i = 0, \forall i$, escapement and thus total fishery profits are identical to the uncoordinated case, while if $\alpha_i = 1, \forall i$, escapement and total fishery profits are identical to those of the sole-owner. But how does the profile of escapements under partial unitization ($0 < \alpha_i < 1, \forall i$) compare to the profile under a sole owner of the spatially connected renewable resource? We begin by considering the effect of increasing contributions on escapement decisions by patch owners. It seems intuitive that sharing a larger fraction of profits would increase escapement levels as larger contributions lead patch owners to take more account of the spatial externality. This intuition is formalized below:

Proposition 3. *Under Assumptions 1-2, escapement in patch i is nondecreasing in contribution α_j, $\frac{de_i^{\{\alpha,\gamma\}}}{d\alpha_j} \geq 0, \forall i, j$. More precisely,*

(A) $\frac{de_i^{\{\alpha,\gamma\}}}{d\alpha_j} > 0, (i \neq j, D_{ij} > 0)$,
(B) $\frac{de_i^{\{\alpha,\gamma\}}}{d\alpha_j} = 0, (i \neq j, D_{ij} = 0)$,
(C) $\frac{de_i^{\{\alpha,\gamma\}}}{d\alpha_i} > 0$.

[21] While this result is derived from a simplified economic model (constant price, constant marginal harvest cost, no stock effects), we can speculate on whether full unitization would yield similar results in a more complex economic environment. Because full unitization induces each patch owner to choose an escapement level that maximizes total system-wide returns (thereby internalizing spatial externalities), we expect this result to likely hold more generally.

Proof. By the implicit function theorem and Equation 16, the effect of increasing another patch owner's contribution α_j is given by:
$\frac{de_i^{\{\alpha,\gamma\}}}{d\alpha_j} = \frac{-[(1-\alpha_i)b_i+\gamma_i\alpha_i b_i](\gamma_i b_j D_{ij})}{f_i''(e_i^{\{\alpha,\gamma\}})\delta[(1-\alpha_i)b_i D_{ii}+\gamma_i\sum_{j=1}^{N}\alpha_j b_j D_{ij}]^2}$. By the concavity of $f_i(\cdot)$, $\frac{de_i^{\{\alpha,\gamma\}}}{d\alpha_j} >$ 0 when $D_{ij} > 0$ and $\frac{de_i^{\{\alpha,\gamma\}}}{d\alpha_j} = 0$ when $D_{ij} = 0$. The effect of increasing own patch contribution α_i is given by: $\frac{de_i^{\{\alpha,\gamma\}}}{d\alpha_i} = \frac{\gamma_i b_i(\gamma_i-1)\sum_{j\neq i}^{N}\alpha_j b_j D_{ij}}{f_i''(e_i^{\{\alpha,\gamma\}})\delta[(1-\alpha_i)b_i D_{ii}+\gamma_i\sum_{j=1}^{N}\alpha_j b_j D_{ij}]^2}$.
By the concavity of $f_i(\cdot)$, $\frac{de_i^{\{\alpha,\gamma\}}}{d\alpha_i} > 0$ □

The intuition underlying Proposition 3 is that an increase in the contribution increases the dependence of owner i's profits on the performance of spatially connected owners. Thus, owner i will place more weight on how her escapement affects the profits of her neighbors. Heintzelman et al. (2009) consider a similar sharing solution for homogenous agents harvesting a single, common property resource and find that sharing induces an "internalizing effect:" because each agent's return depends on returns generated by others in the sharing agreement, each agent has an incentive to reduce the negative externality imposed on others in the sharing agreement. The spatial metapopulation model we consider retains this intuition about externalities but has some important distinctions compared to the single, common pool in Heintzelman et al. (2009). In the case of a single common pool resource, sharing induces a free-riding incentive in the sense that a resource not harvested by one agent can be harvested by others in the sharing agreement. By contrast, in the metapopulation model with property rights considered here, unharvested stock in one patch *cannot* be harvested by another patch owner, and reductions in fishing effort by patch owners under unitization is driven by the internalization of their spatial externality.

Finally, we consider the effect of an increase in the contribution rule on total fishery profits. We have shown that when $\alpha_i = 1, \forall i$ first-best efficiency is achieved, and when $\alpha_i = 0, \forall i$, escapement decisions and thus fishery profits are identical to those without coordination. Intuitively, moving between these two extremes by increasing the contribution rule should increase total fishery profits. We show that this increase in total fishery profits is strictly monotonic with respect to an increase in contribution rule:

Proposition 4. *Under Assumptions 1-2, an increase in contribution α_i (for any i) strictly increases the present value of the fishery.*

Proof. Under a set of constant escapements $\{e_1, e_2, ..., e_N\}$, the total fishery present value is given by:

$$\pi(e_1, e_2, ..., e_N) = \sum_{i=1}^{N} b_i(x_{i0} - e_i) + \frac{\delta}{1-\delta}\sum_{i=1}^{N} b_i(x_i - e_i), \tag{18}$$

where $x_{i0} > e_i$ is the initial stock and $x_i = \sum_j^N f_j(e_j)D_{ji}$ by Equation 1. The change in total fishery present value due to a change in contribution α_i is simply given by

$$\frac{d\pi}{d\alpha_i} = \sum_{j=1}^{N} \frac{d\pi}{de_j^{\{\boldsymbol{\alpha},\boldsymbol{\gamma}\}}}\frac{de_j^{\{\boldsymbol{\alpha},\boldsymbol{\gamma}\}}}{d\alpha_i}. \tag{19}$$

The second term on the rhs of Equation 19 is positive per Proposition 3. The remainder of this proof demonstrates that total fishery profits are increasing in escapement e_i (when $e_i < e_i^{\mathcal{SO}}$). The differential of total fishery profits defined in Equation 18 is given by $d\pi = \sum_{j=1}^{N} \frac{\partial \pi}{\partial e_j} de_j$ and thus the total change in fishery profits due to a change in escapement e_i is given by:

$$\frac{d\pi}{de_i} = \frac{\partial \pi}{\partial e_i} + \sum_{j\neq i}^{N} \frac{\partial \pi}{\partial e_j}\frac{de_j}{de_i}. \tag{20}$$

By state-separability, $\frac{de_j}{de_i} = 0$, and thus:

$$\frac{d\pi}{de_i} = \frac{\partial \pi}{\partial e_i} = -b_i + \frac{\delta}{1-\delta}(\sum_{j=1}^{N} b_j f_i'(e_i)D_{ij} - b_i), \tag{21}$$

which is independent of $e_j, \forall j \neq i$. The present value of the fishery is maximized when Equation 21 is equal to zero, which yields escapement identical to the sole owner escapement $e_i^{\mathcal{SO}}$ defined in 7. Per Propositions 2 and 3, $e_i^{\{\boldsymbol{\alpha},\boldsymbol{\gamma}\}} < e_i^{\mathcal{SO}}$ when $\alpha_i < 1$, and for $e_i < e_i^{\mathcal{SO}}$, $f_i'(e_i) > f_i'(e_i^{\mathcal{SO}})$ by the concavity of $f_i(e_i)$, and thus $\frac{d\pi}{de_i} > 0$.

□

Thus we have shown that escapement under "partial" unitization (when $\alpha_i < 1\ \forall i$) is inefficiently low and that increasing the contribution α_i increases the efficiency of the fishery. Under full unitization, provided that all patch owners are mandated to participate in the unitization scheme, each patch owner's escapement choice is identical to the first-best choice, regardless of the dividend. However, while the intensive margin decision of escapement is independent of the dividend, the extensive margin decision to participate will clearly depend on this dividend. In the following section, we consider the effects of unitization when participation is voluntary.

5 Unitization with endogenous participation

In oil and gas unitization in the United States, participation is typically mandatory. Mineral rights holders in unitized oil and gas fields are required to share extraction revenues in a fully unitized manner ($\alpha_i = 1\ \forall i$). We have shown that a similar legal obligation might solve the spatial externality problem present for spatially connected renewable resource owners. But we ask whether contractual obligation is necessary for efficiency. Here we endogenize participation decisions in order to determine if unitization need be mandatory in order to produce a first-best efficient outcome.

5.1 Repeated play by patch owners

To explore the individual rationality of participation in the unitization scheme $\{\boldsymbol{\alpha}, \boldsymbol{\gamma}\}$, we couch our bioeconomic model as an infinitely repeated Prisoner's Dilemma game with N members.[22] The relevant per-period payoffs are given below:

$$\Pi_i^C = \gamma_i \sum_{j=1}^{N} b_j(x_j^{\mathcal{F}} - e_j^{\mathcal{F}}), \tag{22}$$

$$\Pi_i^N = b_i(x_i^{\mathcal{F}} - e_i^{\mathcal{UC}}), \tag{23}$$

$$\Pi_i^D = b_i(x_i^{\mathcal{UC}} - e_i^{\mathcal{UC}}). \tag{24}$$

Π_i^C represents the shared profit of cooperation when all players choose the fully efficient escapement levels $e_i^{\mathcal{F}}$. Π_i^N represents i's profit from defecting and choosing $e_i^{\mathcal{UC}}$ (and thus not contributing in the unitization scheme) while the other owners play $e_{j\neq i}^{\mathcal{F}}$. Finally, Π_i^D represents i's profit when all owners choose their uncoordinated escapement, $e_i^{\mathcal{UC}}$, i.e. when everyone defects.

There are many potential strategies to consider, and we adopt a Nash reversion strategy to punish defectors. Under this punishment strategy, any defector is punished forever by all other owners reverting to $e_i^{\mathcal{UC}}$. Here, if owner i defects during period t, she will enjoy the fruits of her defection in that first period, and will be 'punished' by every other owner defecting in the subsequent periods. Thus, we can calculate the dynamic benefits of cooperation and defection as follows. The present value of profits from cooperation forever are the discounted sum of Π_i^C:

[22] By contrast, Heintzelman et al. (2009) explore participation incentives in a static model with coalition formation.

$$
\begin{aligned}
J_i^C &= \Pi_i^C + \sum_{t=1}^{\infty} \delta^t \Pi_i^C \\
&= \frac{1}{1-\delta} \gamma_i \sum_{j=1}^{N} b_j (x_j^{\mathcal{F}} - e_j^{\mathcal{F}}).
\end{aligned} \tag{25}
$$

Defection amounts to choosing the uncoordinated escapement of $e_i^{\mathcal{UC}}$, which leads to a steady-state defection stock of $x_i^{\mathcal{UC}}$. Thus, the present value of profit to owner i from defecting is:

$$
\begin{aligned}
J_i^D &= \Pi_i^N + \sum_{t=1}^{\infty} \delta^t \Pi_i^D \\
&= b_i (x_i^{\mathcal{F}} - e_i^{\mathcal{UC}}) + \frac{\delta}{1-\delta} b_i (x_i^{\mathcal{UC}} - e_i^{\mathcal{UC}}).
\end{aligned} \tag{26}
$$

The first term represents the first period benefit of defection (choosing the uncoordinated level of escapement while every other owner is still playing cooperatively), while the second represents the discounted stream of benefits from the steady-state uncoordinated equilibrium. Given the history of play, each owner will consider her profit taking as given the escapement of other owners. In essence, owners will consider the short-term benefits of defection versus the long-term difference in profits between sharing a cooperative equilibrium and going it alone. If we find conditions under which $J_i^C \geq J_i^D$ for all owners i, then unitization is efficient and supportable as a subgame perfect Nash Equilibrium. Whether this occurs will depend on the design of the unitization scheme. Because efficiency requires $\alpha_i = 1 \; \forall i$ (Propositions 2 and 3), we focus on the importance of the set of dividends $\boldsymbol{\gamma} = [\gamma_1, \gamma_2, ..., \gamma_N]$.

5.2 Patch-specific dividends

We leverage the fact that our unitization scheme allows the dividends γ_i to vary across patch owners. The key question here is: Does a set of dividends exist that 1) encourages full participation and 2) is feasible? In considering this question, the result in Corollary 1 becomes crucial. Because harvest efficiency by each patch owner is independent of γ_i, we can consider the minimum γ_i, denoted $\hat{\gamma}_i$, such that patch owner i would prefer cooperation (equation 25) to defection (equation 26). As long as $\sum_i^N \hat{\gamma}_i \leq 1$, the share structure is feasible and yields first-best efficiency for the fishery.

From Equation 25 and Equation 26, the minimum dividend $\hat{\gamma}_i$ for owner i requires:

$$\frac{1}{1-\delta}\hat{\gamma}_i \sum_{j=1}^{N} b_j(x_j^{\mathcal{F}} - e_j^{\mathcal{F}}) = b_i(x_i^{\mathcal{F}} - e_i^{\mathcal{UC}}) + \frac{\delta}{1-\delta} b_i(x_i^{\mathcal{UC}} - e_i^{\mathcal{UC}}). \qquad (27)$$

Solving for $\hat{\gamma}_i$ gives the indifferent dividend for patch i:

$$\hat{\gamma}_i = \frac{b_i((1-\delta)x_i^{\mathcal{F}} + \delta x_i^{\mathcal{UC}} - e_i^{\mathcal{UC}})}{\sum_{j=1}^{N} b_j(x_j^{\mathcal{F}} - e_j^{\mathcal{F}})}. \qquad (28)$$

To explore the determinants of $\hat{\gamma}_i$, we will adopt the following approach. Consider a spatially connected renewable resource with N patch owners, and focus on two such owners, labeled i and j. What characteristics of these patch owners lead to high, or low, values of $\hat{\gamma}_i$ and $\hat{\gamma}_j$? To answer this question, we isolate effects by holding in common all characteristics between patches i and j, save one. We define the following conditions:

Condition 1. *Patches i and j have "equi-inflow" if $D_{ki} = D_{kj}$ for all k.*

Condition 2. *Patches i and j have "equi-price" if $b_i = b_j$.*

Condition 3. *Patches i and j have "equi-production" if $f_i(e) = f_j(e)$.*

Condition 4. *Patches i and j have "equi-retention" if $D_{ii} = D_{jj}$.*

We are interested in comparing $\hat{\gamma}_i$ to $\hat{\gamma}_j$. We begin by noting that the denominator for $\hat{\gamma}_i$ from Equation 28 is the same as the denominator for $\hat{\gamma}_j$. Whether $\hat{\gamma}_i \lesseqgtr \hat{\gamma}_j$ requires considering only the numerators:

$$b_i((1-\delta)x_i^{\mathcal{F}} + \delta x_i^{\mathcal{UC}} - e_i^{\mathcal{UC}}) \lesseqgtr b_j((1-\delta)x_j^{\mathcal{F}} + \delta x_j^{\mathcal{UC}} - e_j^{\mathcal{UC}}) \qquad (29)$$

We derive and will subsequently make use of the following lemmas:

Lemma 2. *Under Conditions 3 and 4, $e_i^{\mathcal{UC}} = e_j^{\mathcal{UC}}$.*

Proof. This follows from Lemma 1, and invoking Conditions 3 and 4. □

Lemma 3. *Under Condition 1, $x_i^{\mathcal{F}} = x_j^{\mathcal{F}}$ and $x_i^{\mathcal{UC}} = x_j^{\mathcal{UC}}$.*

Proof. Equation 1 implies that $x_i = f_1(e_1)D_{1i} + f_2(e_2)D_{2i} + ... + f_N(e_N)D_{Ni}$ and $x_j = f_1(e_1)D_{1j} + f_2(e_2)D_{2j} + ... + f_N(e_N)D_{Nj}$. For any set of escapements $e_1, e_2, ..., e_N$, these are equal by Condition 1. □

These facts give rise to the following propositions regarding the characteristics of patches that determine the dividend required to induce voluntary participation.

Proposition 5. *Suppose that Conditions 1, 3, and 4 hold, and $b_i > b_j$, then $\hat{\gamma}_i > \hat{\gamma}_j$.*

Proof. Under the assumed Conditions, Lemmas 2 and 3 hold, so the only difference in the numerator is b_i and b_j. The result $\hat{\gamma}_i > \gamma_j$ follows trivially. □

Proposition 6. *Suppose that Conditions 1, 2 and 3 hold, and $D_{ii} > D_{jj}$, then $\hat{\gamma}_i < \hat{\gamma}_j$.*

Proof. By Lemma 3 and Condition 2, comparing the numerator requires only comparing $-e_i^{\mathcal{UC}} \lesseqgtr -e_j^{\mathcal{UC}}$. From Lemma 1, and invoking Condition 3 and the assumption about retention, $e_j^{\mathcal{UC}} < e_i^{\mathcal{UC}}$, and therefore, $\hat{\gamma}_i < \hat{\gamma}_j$. □

Proposition 7. *Suppose that Conditions 1, 2, and 4 hold, and $f_i'(\bar{e}) > f_j'(\bar{e})$ $\forall \bar{e}$, then $\hat{\gamma}_i < \hat{\gamma}_j$.*

Proof. By Lemma 3 and Condition 2, we need only to compare $-e_i^{\mathcal{UC}} \lesseqgtr -e_j^{\mathcal{UC}}$. From Lemma 1, and invoking Condition 4 and the assumption about growth, $e_j^{\mathcal{UC}} < e_i^{\mathcal{UC}}$, and therefore, $\hat{\gamma}_i < \hat{\gamma}_j$. □

The intuition underlying Proposition 5 is straightforward: patches with a higher price or lower marginal cost of harvest (higher b_i) require a larger dividend γ_i of total fishery profits to discourage defection. Proposition 6 hinges on the fact that patches with less self-retention (smaller D_{ii}) will harvest to a lower level of escapement when defecting, making initial defection more profitable relative to patches with higher self-retention. Proposition 7 reveals a counterintuitive result on the minimum dividend required to entice patch owners into the unitization scheme. In contrast to Proposition 5 which found that more economically productive patches require larger dividends, Proposition 7 shows that more biologically productive patches (higher $f_i'(\bar{e})$ $\forall \bar{e}$) require smaller dividends to encourage participation. This result follows from the fact that patches with higher productivity will choose higher levels of escapement when defecting, decreasing the benefit of initial defection and thus requiring a smaller dividend to entice cooperation.

In order for the dividend structure described by Equation 28 to be feasible, the individual dividends must sum to less than unity:

$$\frac{\sum_{i=1}^{N} b_i((1-\delta)x_i^{\mathcal{F}} + \delta x_i^{\mathcal{UC}} - e_i^{\mathcal{UC}})}{\sum_{j=1}^{N} b_j(x_j^{\mathcal{F}} - e_j^{\mathcal{F}})} \leq 1. \tag{30}$$

This leads to our next proposition regarding the efficiency of unitization under voluntary participation:

Proposition 8. *Under Assumption 1, there exists a discount factor $\tilde{\delta} < 1$ such that for any $\delta \geq \tilde{\delta}$, full unitization with endogenous participation is supportable, and first-best, economically efficient harvest can be achieved.*

Proof. The denominator of Equation 30 is simply the first-best value of the fishery in steady state. If $\delta = 1$, the numerator is equal to the value of the fishery in the absence of unitization, and as this is less than the first-best value of the fishery, the ratio in Equation 30 is strictly less than one. On the other hand, if $\delta = 0$, the numerator is strictly greater than the denominator, as $e_i^{\mathcal{UC}} < e_i^{\mathcal{F}}$ and the ratio is strictly greater than one. Thus, by the intermediate value theorem, there exists some $0 < \tilde{\delta} < 1$ such that the ratio in Equation 30 is equal to one. For $\delta \geq \tilde{\delta}$, the dividend given by Equation 28 is feasible and full participation with full unitization is supportable, yielding first-best outcomes per Proposition 2. □

This finalizes our main result: by generalizing the concept of unitization, we have shown that fully efficient exploitation can be voluntarily achieved by completely self-interested patch owners and that this result does not require infinite patience.

5.2.1 Alternative strategy considerations

Our result relies on Nash reversion as a means to punish defectors. It may be worth considering punishment strategies other than Nash reversion. One shortcoming of Nash reversion is that it is not renegotiation proof (Van Damme, 1989) and punishers may have an incentive to ‘let bygones be bygones’ and allow a defector back into the cooperative and resume profit sharing. An extension that considers the potential of renegotiation proof strategies (such as Bhat and Huffaker (2007) and Cave (1987)) or more sophisticated punishment strategies (as in Tarui et al. (2008)) in unitized spatially connected renewable resources may prove insightful.

5.2.2 Practical considerations

In the above analysis, the dividend was allowed to vary across patches. However, as a practical matter, such varying shares may be difficult for owners to agree upon. Fish harvested in patch i may come from larvae produced by stock in patch j, which may make agreement on unit shares difficult to come by. Wiggins and Libecap (1985) and Libecap and Wiggins (1985) detail contracting issues in oil unitization, emphasizing the difficulties of unit share agreement as a result of imperfect information. The biological systems underlying renewable resources may make the process of agreeing on unit shares even more contentious.[23]

We also note that unitization may have practical benefits relative to other coordination mechanisms. Because the privately optimal level of escapement in each period (conditional on participation in the unitization agreement) is identical to the sole owner level of escapement, private patch owners have no incentive to deviate from the optimal level of escapement. By contrast, under a coordination mechanism that relies on voluntary collusion (for example, each patch owner agreeing to voluntarily escaping e_{it}^{SO}), each patch owner has a consistent incentive to "cheat" on their agreed-upon level of escapement.[24]

6 Conclusions

Spatial connectivity of renewable resources induces a spatial externality in extraction. For this reason, spatial property rights alone are insufficient to solve the commons problem. We generalize the notion of unitization, developed to

[23] Libecap and Wiggins (1984) argue that the difficulties of agreeing on a complete unitization contract led many oil fields to adopt prorationing, which created some margins for rent dissipation, but was easier to reach agreement on.

[24] Furthermore, in some circumstances tacit collusion may be unsupportable at any discount factor. For example, if the sole owner level of harvest is effectively zero in a particular patch, it is unlikely that patch owner would voluntarily agree to that level of harvest. By contrast, unitization provides a mechanism to compensate that patch owner for reducing harvest and increasing escapement to the optimal level.

coordinate extraction of common oil and gas fields, to spatially connected renewable resources. This coordination mechanism is framed within a spatial bioeconomic model with a patchy "metapopulation." Patch owners then compete in a dynamic game because owner i's harvest affects all other owners in subsequent periods. Our main result is that unitization can serve to coordinate spatial property rights owners. If designed properly, first-best harvest can be achieved, even in cases when the resource would be completely destroyed in the absence of unitization. The unitization scheme relies on two instruments: an owner-specific *contribution* (the fraction of profits an owner must yield to the common pool) and an owner-specific *dividend* (the fraction of the pool redistributed to the owner). By allowing the unitization scheme to vary by participant (e.g., as a function of patch-specific biological productivity or economic returns), the mechanism can induce voluntary participation by all spatial property rights owners.

The special structure of our difference game allows us to obtain sharp analytical results, but the analysis is not without caveats. There is an implicit assumption throughout the paper that the sole owner would achieve socially efficient harvest. While common in the bioeconomics literature, this is somewhat of a heroic assumption, but it does reduce the complexity of our problem. Incorporating other features such as ecological benefits or varying discount rates into the spatial bioeconomic model presented here may prove interesting.[25] Considering harvest incentives under a more general economic model may also be fruitful, as would considering the case of spatial reserves under spatial property rights. For example, might a patch owner find it optimal to pay another patch owner to completely shutdown harvest in her patch (Costello and Kaffine, 2010)? While we have focused on spatial property rights over renewable resources, this unitization scheme might apply more generally. For example, if property rights are assigned on the basis of allowable fish catch (individual transferable quotas (ITQs)), owners may benefit from coordination on harvest via a unitization mechanism. Owners of ITQ in the crab fishery in New Zealand coordinate via a mechanism similar to this where owners contribute quota share to a cooperative ("Crabco") and profits are redistributed differentially to participants at the end of the season (Soboil and Craig, 2008).

While the unitization scheme presented here yields first-best outcomes under mandatory participation and can yield first-best outcomes under voluntary participation, practical considerations may constrain implementation,

[25] Clark and Munro (1980) consider the case of varying discount factor when the sole owner deviates from the social discount factor. They find that corrective taxes may be necessary to ensure economically efficient behavior.

and unitization structures with less than full participation and less than full unitization may maximize the value of spatial renewable resource extraction.

Appendix: Proof to Lemma 1

We proceed by backward induction for each patch owner. At the end of time the value function is zero: $V_{iT+1} = 0$ for all i. Thus the period T Bellman equation for owner i is simply

$$V_{iT}(\mathbf{x_t}) = \max_{e_{iT}} b_i(x_{iT} - e_{iT}) \tag{31}$$

whose interior solution is straightforward: $e^*_{iT} = 0$. In the final period, each patch owner finds it optimal to harvest his entire stock, regardless of decisions made by other patch owners. Note that the patch-i value function has an analytical solution:

$$V_{iT}(\mathbf{x_t}) = b_i x_{iT} \tag{32}$$

which simplifies analysis in the penultimate period. Employing this result, the period $T-1$ patch i Bellman equation is:

$$\begin{aligned} V_{iT-1}(\mathbf{x_{T-1}}) &= \max_{e_{iT-1}} b_i(x_{iT-1} - e_{iT-1}) + \delta b_i x_{iT} \\ &= \max_{e_{iT-1}} b_i(x_{iT-1} - e_{iT-1}) + \delta b_i \sum_j f_j(e_{jT-1}) D_{ji} \end{aligned} \tag{33}$$

Taking e_{jT-1} as given (for $j \neq i$), the first order condition for owner i implies

$$f'_i(e^*_{iT-1}) = \frac{1}{\delta D_{ii}} \tag{34}$$

Notice that this best response function for owner i is independent of both other owners' choices (e_{jT-1}) and of the state variable ($\mathbf{x_{T-1}}$). In other words, period $T-1$ decisions can be written as a set of pre-determined numbers, e^*_{1T-1}, e^*_{2T-1}, ..., that are independent of decisions made prior to period $T-1$.

This pattern turns out to hold in all preceding periods. Stepping back one more period, the period $T-2$ patch i Bellman equation is:

$$\begin{aligned} V_{iT-2}(\mathbf{x_{T-2}}) &= \max_{e_{iT-2}} b_i(x_{iT-2} - e_{iT-2}) + \delta V_{iT-1}(\mathbf{x_{T-1}}) \\ &= \max_{e_{iT-2}} b_i(x_{iT-2} - e_{iT-2}) + \\ &\quad \delta(b_i(\sum_j f_j(e_{jT-2}) D_{ji} - e^*_{iT-1}) + \delta b_i \sum_j f_j(e^*_{jT-1}) D_{ji}) \end{aligned} \tag{35}$$

where, by the above argument, e^*_{jT-1} are scalars (i.e. they are unaffected by e_{iT-2}). Taking the derivative and setting it equal to zero, the optimal choice for patch owner i is:

$$f'_i(e^*_{iT-2}) = \frac{1}{\delta D_{ii}} \tag{36}$$

This solution holds in all preceding periods, so $f'_i(e^*_{it}) = \frac{1}{\delta D_{ii}}$. Because the optimal choice of e^*_{it} is independent of both e_{jt} (for $j \neq i$) and of $\mathbf{x_t}$, this is both an open loop and a feedback control rule.

What happens if owner k deviates, so e_{kt} is given by some value $\tilde{e}_{kt}$ where $f'_k(\tilde{e}_{kt}) \neq \frac{1}{\delta D_{kk}}$? There may be two effects on owner i's choices. First, it may affect his period t choices. Second, because future stock depends on owner k's period t choice, it may affect owner i choices in periods $t+1$, $t+2$, ...We showed above that e_{it} was independent of period t choices by all other patch owners, so we can rule out contemporaneous effects on patch owner i. But we also showed that in *any* period $t < T$, the optimal choice for owner i was independent of the state $\mathbf{x_t}$, which is the only conduit through which $\tilde{e}_{kt}$ affects owner i into the future. Thus, the deviation by owner k has no effect on owner i's future choices.

Thus, the equilibrium to the uncoordinated spatial owner's problem can be summarized as follows:

$$e^{\mathcal{UC}}_{it} \text{ given by: } \begin{cases} 0 & \text{if } t = T, \\ f'_i(e^{\mathcal{UC}}_{it}) = \frac{1}{\delta D_{ii}} & \text{if } t < T. \end{cases} \tag{37}$$

This striking result is not as simple as it may first appear. Importantly, while deviations from this equilibrium will have important effects on the *payoffs* to all patch owners, they will not affect others' optimal *decisions*. Furthermore, it should be emphasized that deviations from this equilibrium will affect optimal harvest by other patch owners (because escapement is constant, so changes in the state will affect harvest).

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