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Spatial and seasonal equilibrium harvesting in quota-managed multispecies fisheries

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1 Introduction

We introduce a bioeconomic model of a multi-species fishery that is managed with individual transferable fishing quotas. A regulator chooses a seasonal quota prior to the start of harvesting operations. Fishermen decide where – across a spatially heterogeneous regions of the fishing ground – and when – within subperiods of the fishing season – to harvest and land each species' quota. The stock grows and disperses spatially throughout the season in response to growth, natural mortality, variation in habitat quality, and harvest mortality. Harvesting is conducted under a joint technology that exhibits a unique form of costly targeting of individual species (Turner 1995, 1997; Singh and Weninger 2009). Fishermen purchase factor inputs, land harvested output and trade quotas in competitive markets. We derive a recursive competitive equilibrium under rational expectations in which seasonal quota markets clear and factors of production earn their opportunity cost. The contribution of the paper is a model framework and methodology for deriving and evaluating ecological-economic equilibrium outcomes in a complex production environment.

The setting we consider combines (1) multiple fish species with own- and cross-species density dependent growth and dispersion, (2) a joint harvesting technology, whereby cost complementarity across species can induce, under conditions that we define, over-quota discards, and (3) a seasonal tradeable quota regulation. Our motivation for incorporating these factors simultaneously is guided by pragmatism; each is present in real world commercial fisheries and each is considered crucial for effective management of marine resources. For example, studies of bioeconomic equilibrium in quota-managed fisheries have featured single species analyses under spatial heterogeneity or within-season temporal stock heterogeneity. No papers combine these three elements simultaneously.

Our paper contributes to two branches of the fisheries management literature. The first studies natural spatial-temporal diffusion processes, with and without management of various forms (Brock and Xepapadeas (2010); Costello and Polasky, 2008; Sanchirico and Wilen (1999, 2001, 2005); Smith et al., 2009). This literature has featured steady state analysis within in a standard commons framework or optimal regulation that ignores the common-pool nature of fisheries resources. Results often contrast open access outcomes, where property rights are absent, with first best outcomes, the scenario wherein a planner controls all aspects of spatial-temporal harvesting activity.[1] Regulations in actual managed fisheries lie between these two extreme. Individual transferable quotas (ITQs), in particular, grant their owner the right to harvest specified quantities of individual species during a regulatory cycle, typically a calendar year. However, the ITQ property rights do not specify where, within potentially heterogeneous regions of the fishing ground, or when, within subperiods of a fishing season, that fish must be landed. As shown in Clark (1980), Boyce (1996), Costello and Deacon (2007), Valcu and Weninger (2013), and others the incomplete property right inherent in an ITQ regulation fosters

[1] Clark (1980) recognized early that first-best harvest outcomes are not generally replicated under an ITQ regulation if a fishery has heterogeneous stock abundance. Costello and Deacon (2007) and Valcu and Weninger (2013) characterize second-best management of a temporally heterogenous, single-species fishery with a time-independent quota regulation. Sanchirico and Wilen (1999, 2001, 2005) examine implications of managing spatially heterogenous (also single-species) fisheries under open access and input-control regulatory approaches. Studies of multi-species, ITQ-regulated fishing under spatial and temporal stock heterogeneity have, to our knowledge, not appeared in the literature.

inefficiency where the spatial-temporal distribution of individual species' harvests deviate from their first-best counterparts. The equilibrium outcomes we derive also differ from the first best. However, our focus is not on efficiency loss due to incomplete property rights, but rather their implications for managing a multiple-species fishery with a quota regulation.

We contribute to a second growing literature that utilizes computer-based models to track complex ecological relationships typically at small spatial and temporal scale.[2] These efforts are part of a broader push to adopt a holistic approach to managing the multiple services provided by marine ecosystems; a management philosophy termed ecosystem-based fisheries management (EBFM).[3] We contend that a shortcoming of the typical computer-based EBFM model is that the main cause of fish mortality, commercial and recreational fishing, is assumed to be either exogenous to the ecological processes of the model, or if endogenously determined, to be guided by *ad hoc* behavioral rules that ignore key technological constraints, and most importantly, the equilibrium market forces that are operational under a quota regulation.[4]

Our model also relaxes restrictive assumptions for the structure of multi-species harvesting technologies. While exceptions exist,[5] studies of multi-species fisheries regulation and management have assumed that commercial fishing technologies (1) are non-joint in inputs, i.e., harvest of individual fish species are made independently of the harvests of other species, or (2) exhibit no control over the mix of harvested species, i.e., Leontief in the harvested output. Both assumptions depart markedly from reality wherein commercial fishermen, through their choice of fine-scale fishing locations, depth and the time of day that gear is set, configuration of bait and hook types, for example, are able to endogenously control the quantity and mix of harvested species. The technological assumptions that have dominated the multiple species literature therefore ignore endogenous behavioral response to changing stock conditions, prices, and regulations.

Our third and perhaps most important departure from the bulk of the fisheries management literature is our assumptions that fishermen are rational economic agents who seek to maximize private fishing profits within the ecological, technological, market, and regulatory

[2]Prellezo, et al., 2009 review 13 bioeconomic models which have been developed primarily for evaluating management of European fisheries. Plagányi, 2007 reviews a larger number of models that seek to improve EBFM.

[3]EBFM is described in Patrick and Link (2015) as one that "Recognizes the combined physical, biological, economic and social tradeoffs for managing the fisheries sector as an integrated system, specifically addresses competing objectives and cumulative impacts to optimize the yields of all fisheries in an ecosystem."

[4]The Atlantis ecosystem model (Fulton et al., 2007) is a computer-based "simulation modeling approach for marine ecosystems that includes oceanographic, chemical (nutrient cycling), ecological (competition and predation), and anthropogenic processes in a three-dimensional, spatially explicit domain. Atlantis is intended as a strategic management tool to evaluate hypotheses about ecosystem response, to understand cumulative impacts of human activities, and to rank broad categories of management options." Fishing behavior is assumed to myopically respond to profit opportunities which are linked in *ad hoc* ways to stock abundance and capital costs. Bioeconomic models that exploit rational economic behavior under real world regulatory instruments have not been developed.

[5]A large literature has evaluated the multi-product commercial fishing technologies, and the implications of the jointness property for sustainable management of fisheries resources (e.g., Squires 1987a, 1987b, 1988). Turner (1995, 1997) and Singh and Weninger (2009) specify joint multiple-species technologies that exhibit the property of weak output disposability and costly targeting of individual species. See Branch and Hilborn (2008) and Singh and Weninger (2017) for empirical evidence to support these technological assumptions.

constraints in which they operate.[6] A rational expectations, seasonal fishing plan must anticipate species-specific stock conditions, landings prices, and quota trading prices, across space and time. We derive rational ecological-economic equilibrium outcomes that satisfy a required equi-marginal principle whereby the profit per unit of quota is equalized across space and throughout the regulatory cycle, i.e., in equilibrium, there can be no quota rent *hot spots*. The equilibrium ecological-economic outcomes we predict differ sharply from computer based bioeconomic models, which typically feature ecological sophistication but exogenous and arbitrary harvesting behavior.

Operationalizing the no hot spot principle with multiple species, locations, and within-season time steps is analytically and computationally challenging. We define and characterize necessary conditions for an ecological-economic equilibrium under quota regulations. We solve for equilibrium outcomes from the perspective of a commune that takes the aggregate stock dynamics as given and then chooses capital, harvests, landings and discards to maximize its seasonal profits. We make significant progress in characterizing equilibria outcomes analytically across species, space and time. We also exploit a novel numerical algorithm to solve for equilibrium outcomes under a host of ecological-economic parameterizations of our model, and under varying quotas. Numerical results are presented in a series of graphs that map quotas to outcomes of management interest, e.g., fishing mortality, economic rent generation.

Our results illustrate complex linkages between the marine ecology, technology, markets, and regulations. The high dimensionality of our model, even in the simple case of two species, two fishing regions and two subperiods of a fishing season, allows us to address a multitude of management-relevant questions. Detailed responses are provided below on a case by case basis. Perhaps the most important insight for purposes of setting seasonal quotas is the combined and simultaneous impacts of a quota on the seasonal ecological-economic equilibrium. For example, a change in a single-species seasonal quota, a species-specific price, or a factor input price will simultaneously alter spatial and intra-season stock conditions, capital allocations, harvests, landings, and discards of individual species. Failure to understand and anticipate these effects pose a significant obstacle for effective management of multiple-species fisheries. Overall, our model and results provide important guidance for quota-based management in coupled ecological-economic systems.

The remainder of the paper is organized as follows. Section 2 presents our model. Section 3 characterizes equilibrium outcomes across heterogeneous regions and subperiods within a regulatory cycle or season. Equilibrium harvests, landings, discards and capital allocations are presented to illustrate implications of varying quota regulations, ecological conditions, e.g., variation in spatial stock distribution and growth characteristics, economic conditions, e.g., varying landings and factor input prices. The final section 4 summarizes our main findings and their implications for the management of multiple-species fisheries.

[6] Berck and Perloff (1984) derive a rational expectations entry equilibrium in an open access fishery. Analytical and computational challenges that arise under rational expectations assumptions may explain why few other papers take this approach.

2 The Model

We use subscript $s = 1, 2, \dots, S$ to denote S distinct regions in a fishery. There are $i = 1, 2, \dots, I$ fish species. Regions are heterogeneous either in terms of their ecological habitat and therefore potential for stock growth, their economic characteristics, e.g. cost of accessing the resources, or both. A fishing region may support some or all species. The bulk of what follows will consider a single representative fishing *season*. Much of the analysis is concerned with the spatial and within-season temporal distribution of harvesting activity. We therefore divided the single season of length T into subperiods, indexed $t = 1, 2, \dots, T$.

The fishery is managed with a individual transferable quotas (ITQs). A regulator announces a quota vector denoted by $Q_0 \equiv \{Q_{i0}\}_{i=1}^{I}$ that caps seasonal landings of each of he I species. There are no restrictions on where or when species i fish can be landed. Landings must match quota holdings.

Harvesting is carried out by a large number of fishermen or fishing firms. Factor inputs and harvested output markets are assumed to be competitive. Quota is traded in frictionless markets, i.e., there are no trading transactions costs.

Fishermen have access to a common harvesting technology. Each active fisherman employs a single unit of vessel capital which carries a subperiod capital opportunity cost, which we denote ρ_s in regions s. Variable harvesting costs depend on the quantities of species harvested and the absolute and relative abundance of the individual species stocks. Stock abundance and species mix can vary across regions and subperiods and therefore so can variable costs. We describe spatial-temporal stock growth conditions in detail below.

The assumption of a common technology allows us to think of a *representative* fishermen in region s. Harvest, landing, and discard choices are assumed identical for all fishermen operating in the same region and also indexed with subscript s.

Trade in quotas ensures that fish are harvested and landed in regions and subperiods where it fetches the highest per unit net revenue. Yet, fishermen do not internalize how their harvesting and discard choices affect current and future stock abundance, i.e., consistent with our competitive market assumption, we assume individual fishermen believe that their own contribution to stock depletion is insignificant relative to the actions of the mass of fishermen.

If the fishery were owned by a single individual, hereafter the *planner*, harvests and landings across species, regions and subperiods would be chosen to maximize fishery value within each season and across seasons, since current seasonal fishing mortality will determine future abundance. Our analysis will abstract from the inter-seasonal quota choice, i.e., we take the quota vector Q_0 as given and focus attention on spatial-temporal harvesting activity in a decentralized fishery that is managed with an ITQ regulation.

The optimal within-season equilibrium choices comprise (a) how much of the seasonal quota of various species to utilize across subperiods and regions, (b) the quantity of vessel capital to employ across subperiods and regions, and (c) the harvest, discard and landing vectors for each unit of capital/vessel (in each region and subperiod).

Before we begin our analysis, it is worth noting that our model is focused on fishing mortality that derives from commercial harvesting operations that are conducted under the operating rules implicit in an ITQ regulation. The role of recreational fishing is ignored, or alternatively assumed exogenous to our model and subsumed in the stock transition equations that we introduce below. Derivation of a recursive equilibrium that includes the recreational fishing sector is reserved for future work.

2.1 A fishing commune's problem

A within-season equilibrium can be replicated through a fishing *commune's* problem in which the commune takes aggregate stock conditions, capital prices, and consumer demand for fish as given, in the sense that the commune assumes these variables are not influenced by the commune's choices. However, when it comes to quota utilization, the commune behaves as a sole owner of *quotas* and allocates them across subperiods and across regions in the most value- and cost-efficient manner.

Note that the cost-minimizing harvest-mix may contain harvests that exceed permissible seasonal landings. Such overages must be discarded to comply with the regulation. The commune does not care precisely about this waste because, as we assume, its goal is to maximize *seasonal* profit given quota Q_0, i.e., we assume the planner but not the commune is concerned with inter-seasonal stock abundance and long term fishery value. It bears emphasis that while the commune construct obtains the same equilibrium outcome as under a decentralized ITQ equilibrium, the former problem is more convenient to formulate and avoids notational clutter.

In what follows, we use small case letters to describe the individual fishermen's variables and capital letters to describe aggregate variables. Let h_{ist}, l_{ist} and d_{ist} denote non-negative harvests, landings, and discards of species i fish for a representative fishermen in region s and subperiod t. Note that $d_{ist} = h_{ist} - l_{ist}$. We use N_{st} to denote the units of capital deployed in region s, subperiod t and ρ_{st} to denote capital cost. Hereafter, vessels and fishermen will be used synonymously.

Let p_{ist} denote the market price of species i landings in region s, subperiod t. The I-dimension vectors of harvests, landings, and discards and prices are denoted h_{st}, l_{st}, d_{st}, and p_{st} respectively. We allow for the case where the landings price depends on its own as well as its substitute species' aggregate landings/supply; $L_{st} \equiv \{L_{ist}\}_{i=1}^{I}$. We will also for simplicity consider the case where the landings prices is fixed. This dependence will be made explicit as needed for clarification.

As is standard in the renewable resources literature, variable costs are assumed to be increasing and convex in harvest, h_{st}, and non-increasing in the stock abundance, X_{st}. We assume in addition that variable harvest costs are non-decreasing in aggregate harvest H_{st}. Dependence on H_{st} captures the effect of contemporaneous harvest on subperiod stock abundance and thus variable cost through the standard stock effect, i.e., nontrivial H_{st} will reduce abundance in region s and subperiod t and thus raise variable costs.[7]

[7] Discrete time models of fisheries exploitation are complicated by the fact that stock growth is a continuous process, while an ITQ regulation specifies seasonal landings limits. Our model strikes a compromise between notational simplicity and accuracy. For example, if there is no within subperiod stock growth, which we assume to be the case, per vessel variable costs may be more accurately defined as,

$$c(h_{st}, X_{st}) = \int_0^{h_{st}} c(z, X_{st} - N_{st} z) dz,$$

where X_{st} is the beginning subperiod stock abundance and z is a variable of integration. Smith (1968) and others consider the possibility that variable harvesting costs depend also on the quantity of capital deployed, The harvest technology is assumed to exhibit the unique form of weak output disposability that imparts *costly targeting* of individual species (Turner 2005; Singh and Weninger 2009, 2017). We assume costs attain a minimum when the mix of harvested species aligns with the mix of stocks in the region and subperiod of fishing. A two species example motivates this property. Suppose region and subperiod (s,t) stock of species 1 is more abundant than species 2. It should then be less costly to harvest a relatively higher quantity of species 1 than, say, equal amounts of both species. The cost savings arise because by targeting a mix that mirrors the relative stock abundance, costly searching and/or gear and bait modifications that my otherwise be required to intercept additional species 2 or avoid the more abundant species 1 are avoided. Note also that if the regulator sets quotas that do not match their relative stock abundance, e.g., suppose the quota for species 1 is relatively small despite its relative abundant stock, the marginal cost of harvesting species 1, evaluated at the regulated quota mix, could be negative. In this scenario, Increasing species' 1 harvest beyond its quota level and discarding the excess catch may actually lower costs since costly actions to avoid species 1 will not be required (see Singh and Weninger (2009) for additional discussion and Singh and Weninger (2017) for empirical evidence).

A functional form that exhibits the stock-dependent costly targeting property is[8]

$$c\left(h,\phi\left(X,H\right)\right)=\left(1+\sum_{j=1}^{I}\gamma_j\left(\frac{h_j}{\sum_{k=1}^{I}h_k}-\frac{X_j}{\sum_{k=1}^{I}X_k}\right)^2\right)\sum_{j=1}^{I}\phi^j\left(X_j,H_j\right)h_j^{\nu}, \tag{1}$$

where the function ϕ is non-increasing in abundance X_{st}, and non-decreasing in aggregate harvest H_{st}.[9] When $\gamma \geq 0$, which we assume, the first bracketed term on the right-hand side of (1) reflects the targeting cost component of the technology. We assume in addition that $\nu > 1$ such that variable costs are increasing and convex in the harvest of each species.[10]

The commune's objective is to maximize seasonal profit by choosing a cross-regional and an intertemporal sequence of vessel capital deployment, harvests, landings, and discards for each representative vessel. Formally, this sequence can be denoted as $\{N_{st},\{l_{ist},d_{ist}\}_i\}_{st}$. The

i.e., $\phi=\phi\left(X_{st},H_{st},N_{st}\right)$ with $\partial\phi(\cdot)/\partial N_{st}>0$. An extension of the model to consider capital congestion effects is reserved for future work.

[8]An alternative specification is

$$c\left(h,\phi\left(X,H\right)\right)=\sum_{j=1}^{I}\left(1+\gamma_j\left(\frac{h_j}{\sum_{k=1}^{I}h_k}-\frac{X_j}{\sum_{k=1}^{I}X_k}\right)^2\right)\phi^j\left(X_j,H_j\right)h_j^{\nu},$$

For the special case $I=2$ both specifications are equivalent.

[9]The function ϕ may be region specific. The results we present are qualitative and they remain unaltered under this modification. For brevity, however, we abstract from this particular form of heterogeneity in this paper.

[10]Note that

$$\frac{h_1}{h_1+h_2}-\frac{X_1}{X_1+X_2}=\frac{h_2}{h_1+h_2}-\frac{X_2}{X_1+X_2}.$$

Hence targeting costs are symmetric across the two species. This need not be the case in general. See Singh and Weninger (2009) for a detailed discussion of the cost function for more than two species and asymmetric targeting costs.

planning problem can be described as

$$\max_{\{N_{st},\{l_{ist},d_{ist}\}_i\}_{st}} \sum_{t=1}^{T}\sum_{s=1}^{S} N_{st}\left(p_{st}\cdot l_{st} - c\left(\underbrace{h_{st}}_{\equiv l_{st}+d_{st}}, \phi\left(X_{st}, H_{st}\right)\right) - \rho_{st}\right)$$

To ensure an efficient allocation of quota across space and time, the commune *internalizes* the laws of motion for all species-specific quotas and subperiods t to $t+1$:

$$Q_{it+1} = Q_{it} - \sum_{s=1}^{S} L_{ist} = Q_{it} - \sum_{s=1}^{S} N_{st} l_{ist} \text{ for all } i, \tag{2}$$

where the second equality follows from $\sum_{s=1}^{S} L_{ist} = \sum_{s=1}^{S} N_{st} l_{ist}$. To solve this problem, the commune must know the sequence of stock abundance across space and time.

It is assumed that the stock abundance of any species in any region in subperiod $t+1$ potentially depends on the escapements of all species across all the regions. Formally, the stock vector across all species and regions follows

$$X_{t+1} = \Gamma\left(E_t\right) \tag{3}$$

where $E_{ist} = X_{ist} - H_{ist}$. To illustrate, let there be two species (1 and 2) and two regions (1 and 2). A simple specification is:

$$X_{11t+1} = E_{11t} + r_{11}E_{11t}(1 - \frac{E_{11t}}{K_{11}} - \alpha_{11}E_{21t}) + \kappa_{11}\left(\frac{E_{12t}}{K_{12}} - \frac{E_{11t}}{K_{11}})\right). \tag{4}$$

r_{11} is an own-stock growth/recruitment parameter; α_{11} captures cross-species competition (if positive) or predation (if negative) on species 1 by species 2 in region 1; κ_{11} captures net regional migration of species 1, and K_{ij} is species and region-specific stock carrying capacity.

We now impose the idea of a rational expectations equilibrium to solve the commune's problem. Such an equilibrium requires that the sequence of stock abundance be consistent with the commune's aggregate harvest choices. Since $H_{ist} = N_{st}h_{ist}$ is the aggregate harvest of species i in region s in subperiod t, it follows that $E_{ist} = X_{ist} - N_{st}h_{ist}$. The equilibrium then requires that abundance X_{t+1} be consistent with the growth specification (4) and the commune's harvest choices.

The problem above is fully specified; the regional and temporal sequence of harvests and landings can be solved for under the rational expectations equilibrium construct. It is however easier to approach this problem as a dynamic program. Let $'$ denote next subperiod variables. The commune's state vector includes current quota holdings and stock abundance: $\{Q, X\}$.

The Bellman equation for the dynamic program is:

$$V_\tau\left(\{Q_i\}_i, \{\{X_{is}\}_i\}_s\right) = \max_{\{N_s, l_{is}, d_{is}, Q_i'\}} \left\{ \begin{array}{c} \sum_{s=1}^{S} N_s\left(p_s \cdot l_s - c\left(h_s, \phi\left(X_s, H_s\right)\right)\right) \\ -\sum_{s=1}^{S} N_s \rho_s + V_{\tau+1}\left(\{Q_i'\}_i, \{\{X_{is}'\}_i\}_s\right) \end{array} \right\} \tag{5}$$

subject to,

$$0 \leq Q_i' = Q_i - \sum_{s=1}^{S} N_s l_{is}; \tag{6a}$$

$$X' = \Gamma(E) \tag{6b}$$

2.2 A recursive equilibrium

Let the current state be denoted as $Y \equiv \{Q, X\} = \left\{\{Q_i\}_i, \{\{X_{is}\}_i\}_s\right\}$. A recursive equilibrium consists of a set of landings, $l_\tau(Y) \equiv \{\{l_{is\tau}(Y)\}_i\}_s$, discards, $d_\tau(Y) \equiv \{\{d_{is\tau}(Y)\}_i\}_s$ (which imply harvests $h_\tau(Y) = l_\tau(Y) + d_\tau(Y)$), vessel deployments, $N_\tau \equiv \{N_{s\tau}\}_s$, landings prices, $p(L(Y))$, and law of motion for $X_\tau'(Y)$ for $\tau = 1, ..., T-1$ such that

1. Given $X_\tau'(Y)$ and $p(L(Y))$, $l_\tau(Y), d_\tau(Y)$, $N_\tau(Y)$ for $\tau = 1, ..., T$ solve the dynamic program (5) subject to (6a) and (6b).

2. Aggregate laws of motion are consistent with policy functions:

   (a) $L_\tau \equiv N_\tau \cdot l_\tau, H_\tau = N_\tau \cdot h_\tau$,

   (b) $Q_\tau'(Y) = Q_\tau - L_\tau(Y)$,

   (c) $X_\tau'(Y) = \Gamma(X_\tau - H_\tau(Y))$, for $\tau = 1, ..., T$.

Characterizing the equilibrium

The Kuhn-Tucker necessary condition for the optimal capital allocation in region s, N_s is,

$$p_s \cdot l_s - c(h_s, \phi(X_s, H_s)) - \rho_s - \sum_i \frac{\partial V_{\tau+1}\left(\{Q_i'\}_i, \{\{X_{is}'\}_i\}_s\right)}{\partial Q_i'} \cdot l_{is} \leq 0. \tag{7}$$

If $N_s > 0$ equation (7) holds with equality.

The necessary condition for regional l_{is} is,

$$p_{is} - c_{h_{is}}(h_s, \phi(X_s, H_s)) - \frac{\partial V_{\tau+1}\left(\{Q_i'\}_i, \{\{X_{is}'\}_i\}_s\right)}{\partial Q_i'} \leq 0, \text{ for } i = 1, ..., I, \tag{8}$$

where $c_{h_{is}}(\cdot)$ denotes partial differentiation with respect to the subscripted argument. If $l_{is} > 0$ equation (8) holds with equality.

Letting λ_i denote the multiplier on the quota constraint for species i, the optimal choice for the quota to be landed in the current period and that to be carried forward, i.e., Q_i' obtains:

$$\frac{\partial V_{\tau+1}\left(\{Q_i'\}_i, \{\{X_{is}'\}_i\}_s\right)}{\partial Q_i'} = \lambda_i. \tag{9}$$

This condition states that the current species i quota shadow price is equal to its marginal value if carried forward. An application of the Envelope theorem for current Q_i obtains

$$\frac{\partial V_{\tau}\left(\{Q_i\}_i, \{\{X_{is}\}_i\}_s\right)}{\partial Q_i} = \frac{\partial V_{\tau+1}\left(\{Q_i'\}_i, \{\{X_{is}'\}_i\}_s\right)}{\partial Q_i'} = \lambda_i. \tag{10}$$

This condition implies that an optimal intertemporal quota allocation equates its marginal value in every period. Otherwise, the commune can increase seasonal fishery rents by allocating quotas towards periods in which its marginal value is higher. Note that in a decentralized equilibrium λ_i will be equal to the equilibrium market (lease) price for a unit species i quota.

Combining the preceding three equations we have for all $\tau \leq T$ and $s = 1, ..., S$:

$$p_{is} - c_{h_{is}}\left(h_s, \phi\left(X_s, H_s\right)\right) - \lambda_i \leq 0. \tag{11}$$

If $l_{is} > 0$ equation (11) holds with equality. This is a standard result equating the marginal net profit from a unit of quota to its shadow price.[11] What is worth noting though is that the condition holds for species i in all regions and within-season subperiods.

Equation (11) affirms that marginal revenue obtains from landings whereas marginal cost depend on harvested quantities. Since landings can not exceed harvests, and discards are nonnegative, optimal discards are characterized by

$$-c_{h_{is}}\left(h_s, \phi\left(X_s, H_s\right)\right) \leq 0. \tag{12}$$

If $d_{is} > 0$, equation (12) hold with equality. The condition for optimal discards can stated alternatively as, $d_{is}c_{h_{is}} = 0$.

Notice that if $c_{h_{is}} < 0$, costs can be lowered by harvesting more species i fish; variable profits rise even if the extra catch is discarded at sea due to insufficient quota. Also, since $p_{is} \geq 0$ for all i for non-binding quotas, $\lambda_i = 0$, condition (11) becomes,

$$p_{is} - c_{h_{is}}\left(h_s, \phi\left(X_s, H_s\right)\right) = 0; \quad d_{is} = 0. \tag{13}$$

This condition states simply that since harvest can be landed to earn positive revenues, there are no discards when the aggregate quota is slack.

Finally, combining (10) and (9) with (7) yields

$$\underbrace{p_s \cdot l_s - c\left(h_s, \phi\left(X_s, H_s\right)\right) - \sum_i \lambda_i l_{is}}_{\pi_s} \leq \rho_s. \tag{14}$$

[11]It is also possible that despite quota being available harvesting of a species at a particular location is prohibitively expensive; $l_{is} = 0$ in all such cases.

If $N_s > 0$ equation (14) holds with equality.

Equation (14) is a free entry equilibrium condition for a decentralized ITQ fishery: variable profit or capital quasi-capital rent in our case, net of quota rent, π_s, must equal the cost of capital. If $\pi_s > \rho_s$, additional capital will enter with accompanying adjustments to l_s and d_s (assuming the quota constraint binds). Capital will exit the fishery again with accompanying adjustments to landings and discards if $\pi_s < \rho_s$.

Solving the commune's problem

The recursive equilibrium is obtained as the solution to $S \cdot T$ optimal capital conditions from equation (7), $I \cdot S \cdot T$ conditions on optimal landings from equation (8), and $I \cdot S \cdot T$ conditions for optimal discards from equation (12). In addition there are I quota constraint conditions. These equations, along with the equilibrium consistency requirements described in section (2.2), solve for (i) $2 \cdot I \cdot S \cdot T$ harvest and landing choices, (ii) $S \cdot T$ capital deployments, and (iii) I quota shadow prices.

In the very simple case with $I = S = T = 2$ there are 8 harvests and landings choices, 4 fleet deployment choices, and 2 quota prices that must be determined. Interactions between the many variables are complex. In the next sections we derive additional insights under some special cases to illustrate implications of the model for fisheries management.

Intensive and extensive cost margins

Consider a region s in which $N_s > 0$. From (12), it follows that either $h_{is} = l_{is} > 0$ or $c_{h_{is}}\left(h_s, \phi\left(X_s, H_s\right)\right) = 0$. Then, (11) implies

$$p_s \cdot l_s - \lambda \cdot l_s = h_s \cdot c_{h_s}.$$

Since $N_s > 0$, the free entry condition (14) obtains;

$$h_s \cdot c_{h_s} = c\left(h_s, \phi\left(X_s, H_s\right)\right) + \rho_s,$$

which essentially reflects an efficiency condition that a competitive equilibrium brings about by linking the *intensive* and *extensive* margins. The right-hand side denotes the cost of an extra vessel (extensive margin) that would catch the vector of harvests h_s. The left-hand side denotes the cost of additional h_s by spreading it over existing vessels (intensive margin). This marginal condition can be summarised as:

Proposition 1: *Variable costs incurred by an active vessel is given by*

$$c\left(h_s, \phi\left(X_s, H_s\right)\right) = \frac{\rho_s}{\nu - 1}. \tag{15}$$

Proof: In appendix 6 we show that $h_s \cdot c_{h_s} = \sum_i h_{is} c_{h_{is}}\left(h_s, \phi\left(X_s, H_s\right)\right) = \nu c\left(h_s, \phi\left(X_s, H_s\right)\right)$. At an optimum that follows (11) - (13), a fisherman's sales revenue net of quota lease cost equals $h_s \cdot (p - \lambda) = h_s c_{h_s} = \sum_i h_{is} c_{h_{is}}$. Since the targeting component of the cost function is homogeneous of degree zero, its contribution to $\sum_i h_{is} c_{h_{is}}$ equal zero. Only the direct (non-targeting) marginal harvest costs matter for the total and net revenue contribution. Notice that the direct component of the cost function has a common exponent ν on all individual species' harvests. Then, the harvest revenue net of variable costs is $(\nu - 1)$ times the latter. Free entry ensures that the net harvest profit equals the capital opportunity cost.

Proposition 1 anchors the fishing costs *for all subperiods* in a fishing season. If the dockside prices are common across regions and are constant within a season, (11) further commands that the marginal costs of each species' harvest $c_{h_{is}}$ be identical across regions and subperiods. An interesting implication is that a fish species with sufficiently low landing quota will be discarded throughout the season. Despite the harmonization of the total costs and each species' marginal costs across time and regions, the equilibrium still allows for cross-species variations across time and region, as will be discussed in the next section.

3 Results

This section derives equilibrium outcomes in a two species, two region fishery case with $T \geq 1$. With $I = 2$, $\frac{h_j}{\sum_{k=1}^2 h_k} - \frac{X_j}{\sum_{k=1}^2 X_k}$ is the same for both j. Hence, letting $\gamma = \gamma_1 + \gamma_2$, the cost function (1) becomes

$$c(h, \phi(X, H)) = \left(1 + \gamma \left(\frac{h_1}{h_1 + h_2} - \frac{X_1}{X_1 + X_2}\right)^2\right) \left(\phi^1(X_1, H_1) h_1^\nu + \phi^2(X_2, H_2) h_2^\nu\right). \quad (16)$$

Note that targeting costs are again relevant and cases may emerge under which harvesting in excess of quotas and discarding overages will lower fishing costs. Optimal equilibrium harvests, discards and landings, continue to be governed by (11) - (13) and proposition 1, and the quota market clearing condition.

3.1 Within-subperiod equilibrium ($T = 1$)

Our goal in this section is to characterize equilibrium harvest, landing, discard, and capital allocation outcomes under different economic and ecological conditions and under varying quotas. For analytical simplicity, we will focus on a two- species, two-region and two-subperiod fishery example for the rest of the paper. Within a fishing season, quota utilizations across different subperiods are facilitated through quota trade and carryovers. The quotas *utilized* within a subperiod operate as if they are the quota *constraints* for that subperiod insofar as they must be consistent with optimality conditions (11) - (13) and the capital allocation condition in Proposition 1. In effect, each subperiod can be studied independently by taking its initial stock conditions and the remaining unfished quota as given. The overarching equilibrium requirement is that (i) the quota prices across all subperiods have to be equal and (ii) the stock available in the second subperiod be consistent with the escapement growth and dispersion from the first subperiod.

With this background, we first examine how quota constraints operate within a single subperiod. Clearly, this analysis also applies if the season comprises of a single subperiod, i.e., $T = 1$. In either case, the problem becomes static; time subscripts are dropped for the remainder of this subsection.

The results we present below are qualitative in nature. However, for graphical presentations, we rely on a specific parameterization of the model. Unless stated otherwise, we assume a symmetric ecology, i.e., common stock growth parameters across species, and common economic conditions across species and regions, i.e., $p_{is} = p$ for all i, s. We specify the function ϕ as $\phi^s(X_s, H_s) = \frac{\eta_s H_s}{X_s}$ where $\eta_s > 0$ is a fixed parameter. Parameter values for our benchmark model are reported in table 1.

Cost and prices		Stock growth
$\gamma = 25$		$r_{is} = r = 1$
$\nu = 1.25$		$\alpha_{is} = \alpha = 0.2$
$\eta = 2.5$		$\beta = 0.05$
$\rho_s = \rho = 0.15$		$\kappa_i = \kappa = 0.1$
$p_{is} = p = 1$		$K_{ij} = K = 0.08$

Table 1: **Benchmark model parameters.**

We will introduce heterogeneity across species, space and time as deviations from steady state values. For both species, let x^* and $Q^* = H^*$ denote the steady state stock abundance and quota that maximize the present value of the fishery, as defined by the parameters in table 1, over an infinite (seasonal) planning horizon. Let N^* denote the equilibrium capital employed in each region. Below we consider scenarios in which initial stock abundance and/or seasonal quotas deviate from these steady state values.

The question we will answer is, what regional harvests, landings and discards emerge in equilibrium under alternative regulations $\{Q_1, Q_2\} \in \Re^2_+$? In other words, we characterize the mapping between quotas and ITQ-equilibrium outcomes of management interest. It should be emphasized that understanding the complete mapping from quotas to regional-temporal fishing mortality is crucial for addressing the problem of choosing seasonal quotas to meet long term management goals. In what follows we derive equilibrium outcomes under varying ecological and economic scenarios chosen to characterize this mapping and showcase key forces in our model.

We have now set the context and pre-conditions for understanding a single-period competitive multi-regional ITQ equilibrium for alternative $\{Q_1, Q_2\} \in \Re^2_+$. To proceed, we first partition the quota space into *zones* that (a) demarcate quota combinations for which landings constraints either bind or are slack and (b) demarcate quota combinations for which the harvest of either of the species is discarded.

Figure 1 shows eight divisions of quota space, hereafter referred to as *zones* that correspond to constraints in equations (11) and (12). Quantities on the axes are scaled as a percentage of a steady state quota that maximizes the value of fishery. Line segments $0A\bar{A}$ and $0C\bar{C}$ delineate discard zones (Singh and Weninger, 2009). The quota for species 1 is slack in zones I, II, and III since the available quota exceeds the unconstrained optimal harvests of species 1. Quota allocations in zones III and IV, identify quotas for which optimal harvests satisfy the necessary condition, $c_{h_{2s}}(h_s, \phi(X_s, H_s)) = 0$ with positive discards of species 2 fish. This occurs because the species 2 quota in zones III and IV is relatively small, i.e., fishing costs can

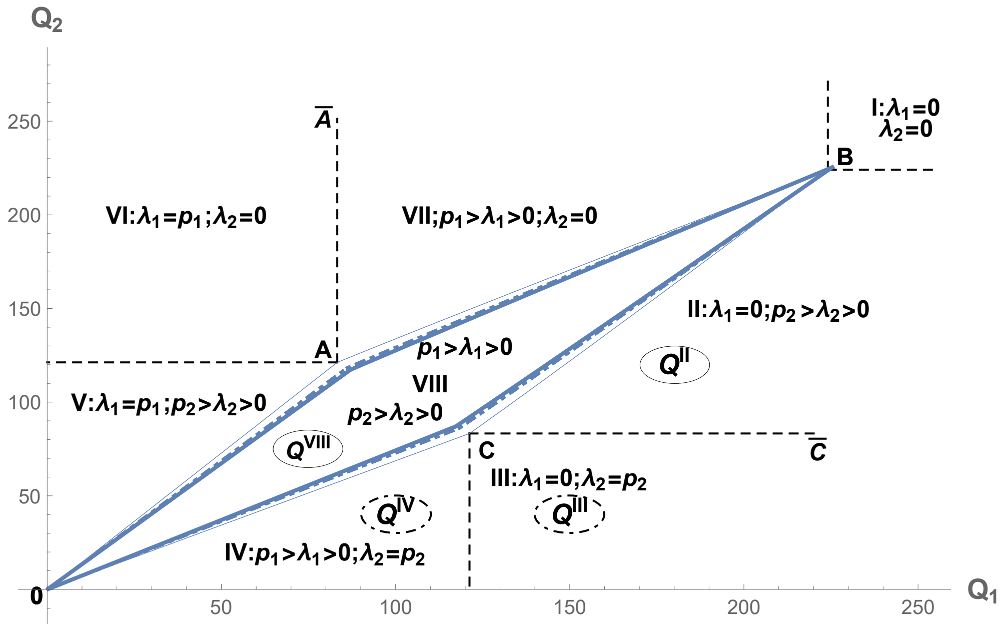
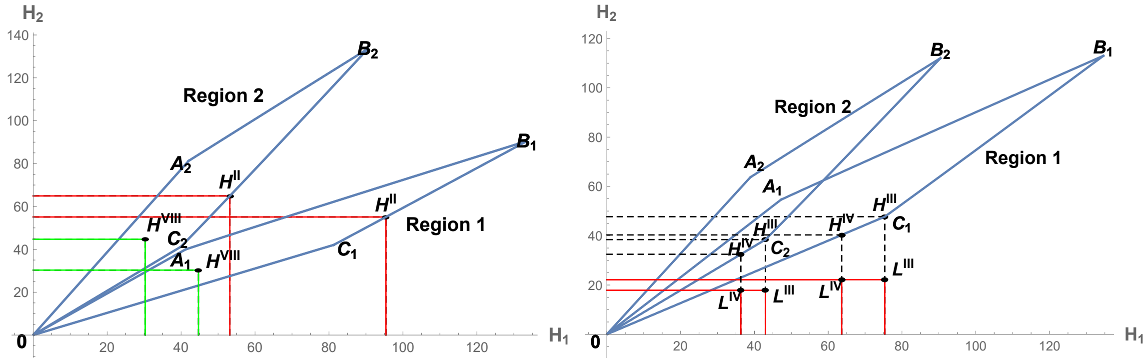


Figure 1: **Equilibrium in an ITQ-Regulated Fishery.** Quotas are denoted as a percentage of the benchmark model steady state values. Zones I - VIII identify quota combinations, $\{Q_1, Q_2\}$, under which landings constraints either bind or are slack and individual species are either retained or discarded at sea.

be reduced by harvesting more than Q_2 and discarding the excess catch. In zone II discards are zero; while species 2 quota remains relatively low, both species quotas are larger (than in zones III and IV). It is profitable to harvest a mix of species that more closely aligns with stock abundance and leave species 1 quota unutilized, i.e., $\lambda_1 = 0$ for $Q \in$ II. For the same reasons (but with species numbers reversed), species 1 discards are positive for $Q \in$ V, VI, and there are no discards when $Q \in$ VII. In zone VIII, both the quotas bind while none of the species is discarded. Importantly, observe that the diamond shaped zone VIII, shown in both figures, is the implementable harvest set identified in Singh and Weninger (2009). The mapping between quotas that fall within the implementable sets shown and equilibrium harvests is one-to-one.

To illustrate the role of stock conditions on equilibrium outcomes, figure 1 shows implementable sets under varying stock conditions. The innermost set demarcated by thick lines represents the optimal symmetric steady state stock, $X^* = \{\{x^*, x^*\}, \{x^*, x^*\}\}$. The outermost set demarcated by a thin line assumes initial abundance, $X = \{\{1.2x^*, 0.8x^*\}, \{0.8x^*, 1.2x^*\}\}$. In this case, region 1 is relatively more abundant in species 1 while region 2 is symmetrically more abundant in species 2. While no region has an *absolute* stock advantage, each has a *comparative* advantage in the extraction of a particular species. The implementable set demarcated by dashed lines assume stock $X = \{\{1.2x^*, x^*\}, \{0.8x^*, x^*\}\}$. In this scenario region 1 exhibits an absolute stock advantage. Also, both regions have a comparative advantage in one of the species but these magnitudes are smaller compared to the the previous scenario.



(a) $X = \{\{1.2x^*, 0.8x^*\}, \{0.8x^*, 1.2x^*\}\}$ (b) $X = \{\{1.2x^*, x^*\}, \{0.8x^*, x^*\}\}$

Figure 2: **Regional Equilibrium Outcomes.** Harvests are denoted as a percentage of the benchmark model steady state values. Stock abundance in panel (a) satisfies $X = \{\{1.2x^*, 0.8x^*\}, \{0.8x^*, 1.2x^*\}\}$; abundance in (b) satisfies $X = \{\{1.2x^*, x^*\}, \{0.8x^*, x^*\}\}$.

Despite the regional stock differences between the three examples, the three fishery wide implementable sets converge closely. This is by construction: in all the three cases aggregate stock abundance is equal at $\{2x^*, 2x^*\}$. The regional differences become salient in the respective regional partitions shown in figure 2.

It is worth reiterating that the equilibrium quota trading prices, λ_1 and λ_2 vary with the quota set by the regulator, initial stock conditions, prices, and model parameters, but are common across regions. Similarly, because dockside prices are assumed common across regions, if either species' harvest is discarded its quota price will equal to its landings price, i.e., $\lambda = p$, and there will be discards in both regions.[12] Therefore, common equilibrium constraint conditions across the two regions facilitates a unique mapping between zones I-VIII in the fishery wide quota partition with similar zones in regional partitions.

Zones I-VIII in figure 1 show aggregate or fishery-wide outcomes. The demarcation of these zones obtain from aggregating equilibrium regional outcomes, whose zonal demarcations are shown in figure 2.

Figure 2a relates to the partition and the implementable set denoted by thin lines in Figure 1. Recall that the ecological scenario we consider includes relative higher species 1 abundance in region 1 with lower cost of harvesting species 1 fish. As a result, for region 1, the set of quotas for which species 1 constraint is slack (zones II and III) and the set of quotas for which species 2 is discarded (zones III and IV) is relatively larger. The situation is reversed in region 2 where species 2 is more abundant and less costly to harvest. Overall, the divergence between the regional implementable sets highlights the assumed species-specific comparative advantages. Both sets however cover the same area, which indicates that neither has an absolute stock advantage.

Figure 2b relates to the implementable set denoted by dashed lines in figure 1. The two regions in figure 2b also exhibit comparative advantage in one species, albeit diminished since

[12]These arguments hold for any number of regions and species; assuming $I = 2$ facilitates a graphical representation.

the regional sets are closer than in figure 2a. A higher area covered by region 1 indicates its absolute advantage.

The eight zones in figures 1 and 2 span all possible constraint combinations in (11) and (12). We next present a complete characterization of harvest and discard behavior in each zone with specific examples illustrated in figures 1 and 2. To ease notation and where no confusion can arise, this section adopts the notational convention $\phi^s = \phi(X_s, H_s)$.

Zone I: Neither species' quota binds; no discards. For quota set in zone I, $\lambda_i = 0$ for $i = 1, 2$. Then, $c_{h_{is}}(h_{1s}, h_{2s}, \phi^s) = p_i$ for all i, s. These conditions along with Proposition 1 solve for the unconstrained per vessel harvests $\{h_{is}\}$ and number of vessels $\{N_s\}$ within each region. Thus, for regions 1 and 2, unconstrained aggregate harvests are obtained at points B_1 and B_2. A simple addition of aggregate harvest vectors corresponding to B_1 and B_2 in 2 then obtains B. Obviously, if the quota of any of the species exceeds its value at B, it will remain slack. This is the logic that identifies zone I in figure 1.

Consequently, any fishery-wide quota that lies in zone I in figure 1 will in equilibrium map to points B_1 and B_2.

Zone II: Species' 2 constraint binds; no discards. If a quota is set in zone II, $\lambda_1 = 0$, $\lambda_2 > 0$. In the absence of discards, $\lambda_2 < p_2$. Here, $c_{h_{1s}}(h_{1s}, h_{2s}, \phi^s) = p_1$ for $s = 1, 2$; $c_{h_{21}}\left(h_{11}, h_{21}, \phi^1\right) = c_{h_{22}}\left(h_{12}, \frac{Q_2 - N_1 h_{21}}{N_2}, \phi^2\right) = p_2 - \lambda_2 \in (0, p_2)$. These conditions along with proposition 1 obtain per vessel harvest vectors $\{h_{is}\}$ and number of vessels $\{N_s\}$ in each region. A simple aggregation obtains total regional and fishery-wide harvest vectors. Each point $\lambda_2 \in (0, p_2)$ lies on the line segment B_1C_1 and B_2C_2 in figure 2. In particular, for $\lambda_2 = 0$ it lies at B_1 and B_2 and for $\lambda_2 = p_2$ it lies at C_1 and C_2. The line segment BC in figure 1 aggregates these regional segments: for each $\lambda_2 \in (0, p_2)$, there is a unique point on the three line segments $\{B_1C_1, B_2C_2, BC\}$. Conversely, a point on BC can be uniquely mapped to points on regional zonal boundaries. Thus, if a fishery wide quota lies in zone II, the total harvest and landing of both species lies on the line segment BC and corresponding regional harvests lie on B_1C_1 and B_2C_2, with $H_{21} + H_{22} = Q_2$. Obviously, $Q_1 > H_{11} + H_{12}$.

Quota point $Q^{II} = \{1.8Q^*, 1.2Q^*\}$ in figure 1 falls in zone II. For the relative stock abundances corresponding to figure 2a, the two regional harvests are at point H^{II} in the respective partitions.[13]

Zone III: Species' 2 constraint binds; positive species 2 discards. For quotas set in zone III we have $\lambda_1 = 0$ and $\lambda_2 = p_2$. Here, $c_{h_{1s}}(h_{1s}, h_{2s}, \phi^s) = p_1$ for all s; $c_{h_{21}}\left(h_{11}, h_{21}, \phi^1\right) = c_{h_{22}}\left(h_{12}, h_{22}, \phi^2\right) = 0$; $Q_2 < H_{21} + H_{22} = N_1 h_{21} + N_2 h_{22}$. These conditions along with Proposition 1 obtain per vessel harvest vectors $\{h_{is}\}$ and number of vessels $\{N_s\}$ in each region. Notice from the above conditions that the equilibrium quantities are independent of $\{Q_1, Q_2\}$ in zone III.

Quota $Q^{III} = \{1.5Q^*, 0.4Q^*\}$ in figure 1 falls in this zone. For the relative stock abundances corresponding to figure 2b, the two regional harvests and landings fall at points H^{III} and L^{III}

[13] $L^{II} = H^{II}$, though not shown in the figure to avoid clutter.

in the respective regional partitions. Species 2 discard occurs as a result. Notice that region 1 harvests a larger share of both species due to its larger stock.

Zone IV: Quotas of both species bind; positive species 2 discards. In zone IV, $\lambda_1 \in (0, p_1)$ and $\lambda_2 = p_2$. Here $c_{h_{11}}\left(h_{11}, h_{21}, \phi^1\right) = c_{h_{12}}\left(\frac{Q_1 - N_1 h_{11}}{N_2}, h_{22}, \phi^2\right) = p_1 - \lambda_1 \in (0, p_1)\,; c_{h_{21}}\left(h_{11}, h_{21}, \phi^1\right) = c_{h_{22}}\left(h_{12}, h_{22}, \phi^2\right) = 0$. Once again, these conditions along with proposition 1 obtain per vessel harvest vectors $\{h_{is}\}$ and vessel allocations $\{N_s\}$ for region s. A simple aggregation obtains fishery-wide harvest vectors. Each point $\lambda_1 \in (0, p_1)$ lies on the line segment $0C_1$ and $0C_2$, with $\lambda_1 = 0$ at C_1 and C_2 and $\lambda_1 = p_1$ at 0 (figure 2). The line segment $0C$ in figure 1 aggregates these two regional segments: for each $\lambda_1 \in (0, p_1)$, there is a unique point on the three line segments $\{0C_1, 0C_2, 0C)\}$. Conversely, a point on $0C$ can be uniquely mapped to the points on its regional counterparts.

Clearly, if the fishery-wide quota lies in zone IV, i.e., the total harvest of both species lies at its *vertical* projection on the line segment $0C$. The corresponding regional harvests lie on $0C_1$ and $0C_2$, with $H_{11} + H_{12} = Q_1$ while $Q_2 = L_{21} + L_{22} < H_{21} + H_{22}$.

Quota point $Q^{IV} = \{1.5Q^*, 0.4Q^*\}$ in figure 1 falls in this zone. For the relative stock abundances corresponding to figure 2b, the two regional harvests and landings fall at points H^{IV} and L^{IV} in the respective regional partitions. Species 2 discard occurs as a result. Unlike zone III, the quota of species 1 is now fully utilized.

Zone V, VI, and VII Equilibrium in zones V, VI, and VII mirrors the equilibrium in zones IV, III, and II respectively, with species' quotas and stocks reversed. We omit the details here to conserve space.

Zone VIII: Both species' quotas bind: no discards. In zone VIII, quota shadow prices satisfy $\lambda_i \in (0, p_i)$. Here $c_{h_{11}}\left(h_{11}, h_{21}, \phi^1\right) = c_{h_{12}}\left(\frac{Q_1 - N_1 h_{11}}{N_2}, h_{22}, \phi^2\right) = p_1 - \lambda_1 \in (0, p_1)$; $c_{h_{21}}\left(h_{11}, h_{21}, \phi^1\right) = c_{h_{22}}\left(h_{12}, \frac{Q_2 - N_1 h_{21}}{N_2}, \phi^2\left(X_2, H_2\right)\right) = p_2 - \lambda_2 \in (0, p_2)$.

Quota point $Q^{VIII} = \{0.75Q^*, 0.75Q^*\}$ in figure 1 falls in this zone. For the relative stock abundances corresponding to figure 2a, the two regional harvests fall at points H^{VIII} inside the implementable sets of respective regional partitions. Both species quotas are fully utilized without any discards: $L^{VIII} = H^{VIII}$.

Regional capital deployment

Equilibrium capital allocations corresponding to quota zones in figures 1 and 2 are shown in figure 3: the allocation set demarcated by $OABC$ corresponds to figure 2a while $OA'B'C'$ corresponds to figure 2b.

When regions are ecologically and economically symmetric, equilibrium capital will also be symmetric. The solid line OB in figure 3 conforms to this case.

Recall that stock abundance in figure 2a, each region has a comparative cost advantage in one species, but neither has an absolute cost advantage. The set $OABC$ indicates that a higher quota of species 1 (2) attracts more capital in region 1 (2) in equilibrium. For

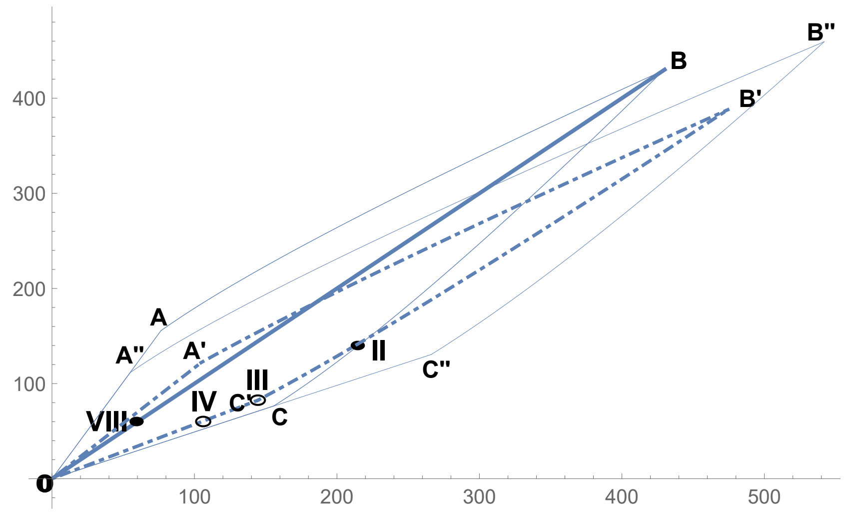


Figure 3: **Equilibrium Capital Allocation.** Horizontal (vertical) axes denote capital allocations as a % of N^* in regions 1 (2). The solid line OB represents $X = \{\{x^*, x^*\}, \{x^*, x^*\}\}$ and $p_1 = p_2 = 1$. The set $OABC$ corresponds to $X = \{\{1.2x^*, x^*\}, \{x^*, 1.2x^*\}\}$ and $p_1 = p_2 = 1; OA'B'C'$ corresponds to $X = \{\{1.2x^*, x^*\}, \{0.8x^*, x^*\}\}$ and $p_1 = p_2 = 1$; $OA''B''C''$ corresponds to $X = \{\{1.2x^*, x^*\}, \{x^*, 1.2x^*\}\}$, $p_1 = 1.5$, and $p_2 = 1$.

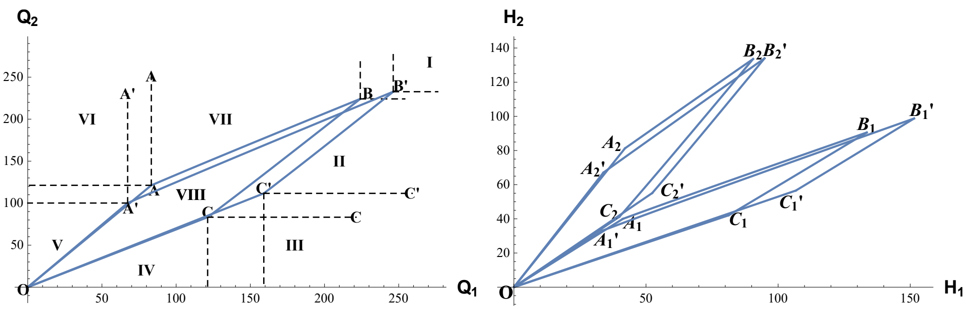
quotas Q^{II} and Q^{VIII} in figure 1 and the two regions represented in figure 2a, the equilibrium capital allocations are at points II and VIII, respectively. On the other hand, for the regions represented in figure 2b, region 1 has 50% more stock of species 1 while both regions have an identical stock of species 2. The set $OA'B'C'$ in figure 3 shows that the capital allocation favors region 1. For Q^{III} and Q^{IV} from figure 1, equilibrium capital occurs at points III and IV, respectively.

Landings prices

We next consider the role of landings prices on the mapping between the quotas and equilibrium outcomes. For this exercise we assume $p_1 = 1.5$ and $p_2 = 1$. The stock conditions are represented by figure 2a. All other parameters are unchanged. Figure 4 contrasts changes in harvest/discard outcomes relative to the benchmark case.

There are four effects of an increase in price of species 1. First, the set of quotas for which the species 1 quota is slack, i.e., zones II and III are now smaller. Second, vice versa, zones VI and VII, i.e., cases where the species 2 quota is slack become larger. These changes result from the increased profitability of species 1 which, under a joint technology, expand the quantity of both species for which variable profits offset capital costs.

The discard set of species 2, the area under $0C'C'$ is enlarged, while the discard set for species 1, $0A'A'$ shrinks. Changes in regional zonal partitions (figure 4b) mimic fishery-wide changes (figure 4a) closely. Region 1, with higher relative abundance of the now higher prices species 1 spans a larger portion of quota space, some of which was unutilized under the lower



(a) Fishery-wide equilibrium (b) Regional equilibrium.

Figure 4: **Landings Price Effects.** Figure shows the impact of a 50 % increase in the landing price of species 1 fish, relative to the baseline parameters. Quotas and Harvests are reported as percentage of benchmark model steady state values. Stock conditions satisfy $X = \{\{1.2x^*, 0.8x^*\}, \{0.8x^*, 1.2x^*\}\}$.

benchmark price.

It is evident that the set of quotas in zones IV and V falling under line segments $0C$ and $0A'$, respectively, are invariant to a change in the price of species 1. Recall that both quotas bind on these segments. For one species, harvest equals quota, whereas for the other (over-quota) species, marginal harvest cost is equal to zero. A change in fish price of species 1 only raises its quota price for quotas set in zones IV and V.[14]

We note that a rise in the price of species 1 increases capital quasi rent particularly region 1 where it is relatively abundant, thus drawing additional capital. The set $OA''B''C''$ in figure 3 illustrates the resultant shift in equilibrium capital allocation.

3.2 Equilibrium across regions and subperiods

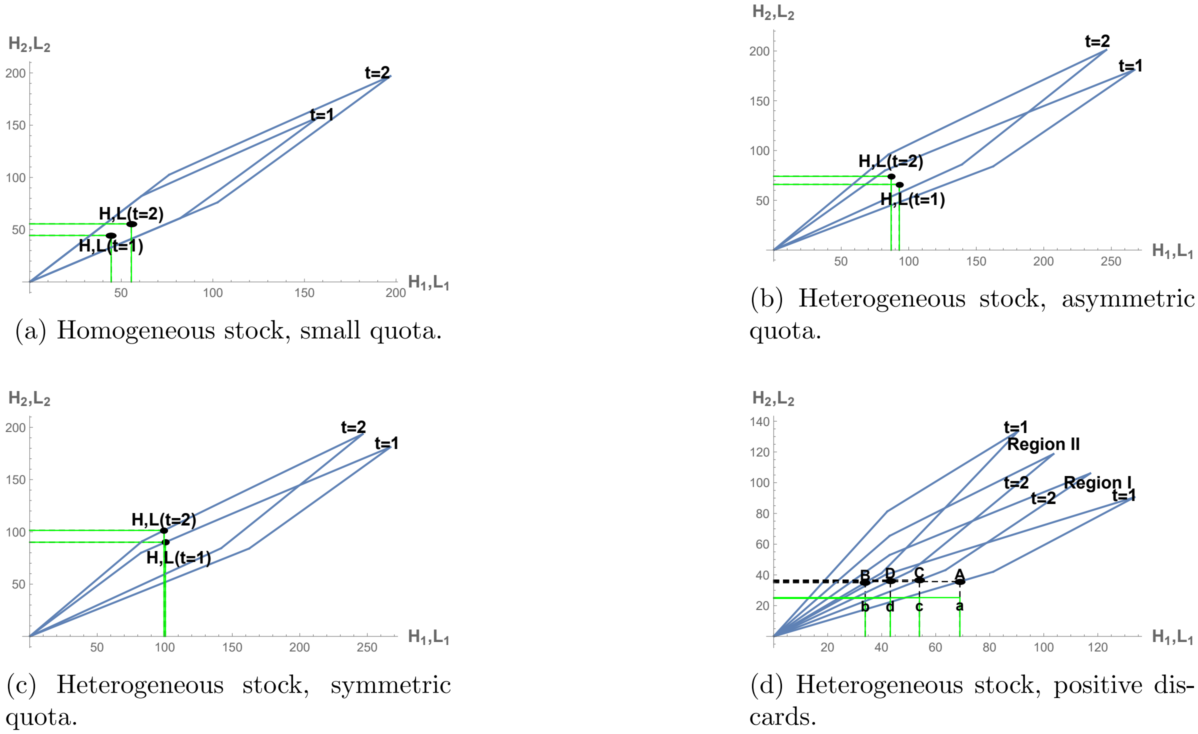
We next characterize the equilibrium spatial and temporal distribution of harvests, landings and quota utilization, and discards. With multiple subperiods temporal quota utilization is endogenous and satisfies the temporal arbitrage condition in equation (10). In the two region case, the quota market clearing equation becomes,

$$\sum_{t=1}^{2} L_{1it} + L_{2it} = \sum_{t=1}^{2} N_{1t} l_{1t} + N_{2t} l_{2it} \leq Q_i, \quad i = 1, 2.$$

It is worth reiterating that given dockside fish prices and quota prices, equations (11) - (13) along with proposition 1 continue to determine equilibrium harvests and landings. With $T = 2$ the quota market clears across regions and subperiods.

A second difference is that stock abundance across multiple subperiods is endogenously determined by spatial, within-season and species-specific harvests. A perfect foresight equilib-

[14]It is easily checked that $p_1 - \lambda_1$ remains constant on the segment $0C$ when p_1 changes from 1 to 1.5 and the segment extends up to $0C'$. With $p_1 = 1$, $\lambda_1 = 0$ at C, but with $p_1 = 1.5$, $\lambda_1 = 0$ at C'. It must be the case that $\lambda_1 = 0.5$ at C so that $p_1 - \lambda_1 = 1$ remains as before at C.



(a) Homogeneous stock, small quota.

(b) Heterogeneous stock, asymmetric quota.

(c) Heterogeneous stock, symmetric quota.

(d) Heterogeneous stock, positive discards.

Figure 5: **Equilibrium under multiple-subperiods.** Harvests and landings are the percentage of benchmark model steady state values. Panel (a) assumes stock abundance $\{0.7x^*, 0.7x^*, 0.7x^*, 0.7x^*\}$, quota $\{Q^*, Q^*\}$; panel (b) assumes abundance $\{1.2x^*, 0.8x^*, 1.2x^*, 0.8x^*\}$, and quota $\{1.8Q^*, 1.4Q^*\}$; panel (c) assumes abundance $\{1.2x^*, 0.8x^*, 1.2x^*, 0.8x^*\}$, quota $\{1.6Q^*, 1.6Q^*\}$; panel (d) assumes $\{1.2x^*, 0.8x^*, 0.8x^*, 1.2x^*\}$, quota $\{2Q^*, Q^*\}$. Subperiods are denoted $t = 1, 2$.

rium requires the dynamic evolution of stock, given by $X_{t+1} = \Gamma(X_t - H_t)$, to be consistent with the spatial-temporal harvest profile. In equilibrium, fishermen rationally forecast harvests and accompanying stock conditions for all s, t.[15] Appendix 7 provides a fixed point algorithm to solve for the equilibrium by using a computer.

In this setting, the shape and location of quota zones discussed above and the implementable harvest sets evolve as stock conditions change throughout the season. We next present equilibrium outcomes under alternate management scenarios to further characterize equilibrium outcomes of management interest.

Stock growth

Figure 5 shows equilibrium harvests and landings under various regulatory scenarios and stock conditions. In each case, $t = 1, 2$ indexes subperiods within the season. Figures 5a, 5b, and 5c

[15]In the model, it is *perfect foresight* that allows fishermen to correctly forecast future stocks. Under uncertainty, a *rational expectations* equilibrium requires that fishermen utilize publicly known stochastic distributions of the model's random variables to form their stock forecasts.

focus on temporal effects in a fishery with homogenous stock conditions across regions. Figure 5d shows a case where regional abundance are different at the beginning of season. The quota regulations vary to illustrate the important determinants of the equilibrium outcomes. Specific are presented below.

Following the notation of the previous section, x^* and Q^* denote species-specific, steady state stocks and optimal subperiod quotas for our baseline fishery. With $T = 2$, the seasonal quota is $2Q^*$ for each species. The results in figure 5a show fishery-wide outcomes for a regionally homogeneous fishery (effectively a single-region fishery) under a tight seasonal quota. The scenario in figure 5a assumes beginning season stocks equal to $\{0.7x^*, 0.7x^*, 0.7x^*, 0.7x^*\}$, and seasonal quota are set at $\{Q^*, Q^*\}$. Thus, stocks are assumed to be 70% of their steady state values and quota is set at 50% of its steady state value. This scenario may represent the case of an low quota chosen to protect an overfished stock.

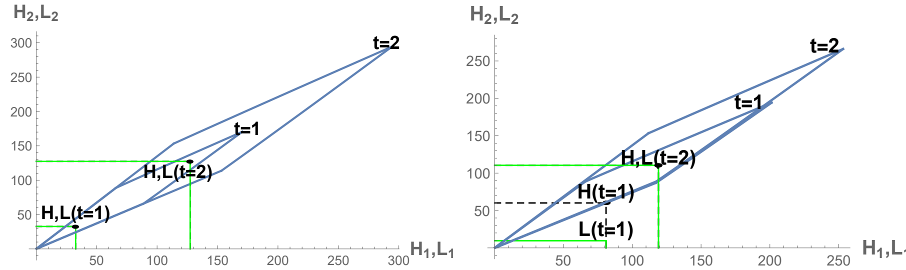
As evident in figure 5a, equilibrium harvest in the first subperiod are less than harvests in the second subperiod. The equilibrium foresees the growth of both species and thus the lower harvesting costs at $t = 2$. Equilibrium capita and harvest per vessel at $t = 1$ and $t = 2$ increase over time while the equilibrium quota price remains constant throughout the season. Note also that the zones that characterize fishing behavior expand reflecting within-season stock growth.

The results reported in figure 5b consider a scenario in which individual stocks deviated from their steady state levels but remain homogeneously distributed across regions. Specifically, we assume initial abundance follows $\{1.2x^*, 0.8x^*, 1.2x^*, 0.8x^*\}$; the species 1 stock is 20% above its steady state value while the species 2 stock is 20 % below its steady state value. We assume seasonal quotas that mirror relative abundance; $\{1.8Q^*, 1.4Q^*\}$.

Figure 5b illustrates how the relative stocks of the two species and their harvests evolve over time. Note first that the $t = 1$ implementable harvest set is tilted toward the more abundant species 1 stock. The ITQ equilibrium induces a lower harvest of less-abundant species 2, and a higher harvest of more-abundant species 1. Escapement at $t = 1$ and stock growth between subperiods aligns the two stocks toward their common steady state value as is evident from the rotation of the implementable set in $t = 2$ counterclockwise toward species 2. At $t = 2$, the species 2 harvest increases while the species 1 harvest falls relative to their $t = 1$ values.

Species-specific quotas either bind or are slack at the seasonal level. Figure 5c assumes initial stock abundance that differs from steady state values, $\{1.2x^*, 0.8x^*, 1.2x^*, 0.8x^*\}$, but with quotas set equally at $\{1.6Q^*, 1.6Q^*\}$. This scenario features a stock-quota mismatch whereby the regulator has issued excess species 2 quota. In figure 5c, the species 2 quota is slack throughout the season. Equilibrium harvests in both subperiods equates the landing price to the marginal cost of are species 2 harvests, since with a slack seasonal quota $\lambda_2 = 0$. As in the scenario above, figure 5b, low species 2 harvests at $t = 1$ allows the species 2 stock growth, which again causes the $t = 2$ implementable harvest set to rotate counterclockwise.

Figure 5d considers a case where species-specific stocks deviate from their steady state values, and are distributed heterogeneously across regions. We assume the beginning season stock abundance is given as $\{1.2x^*, 0.8x^*, 0.8x^*, 1.2x^*\}$ so that both regions have a comparable cost advantage in the harvest of their relatively-abundant species. We assume quota set at $\{2Q^*, Q^*\}$. This scenario is constructed to illustrate conditions under which discarding occurs. Specifically, under a relatively small species 2 quota, targeting species 2 is costly, i.e, costs can be lowered by targeting a mix of species that aligns with abundance and discarding the



(a) Common spatial abundance, symmetric quotas, increasing landings prices.

(b) Common spatial abundance, asymmetric quotas, increasing landings prices.

Figure 6: **Temporal Price Effects.** Panel (a) assumes abundance at $t = 1$ is $\{x^*, x^*, x^*, x^*\}$, quota at $\{1.6Q^*, 1.6Q^*\}$, and landings prices 20% below and 20% above baseline values at $t = 1$ and $t = 2$, respectively. Panel (b) assumes initial stock abundance equal to $\{x^*, x^*, x^*, x^*\}$, quotas set at $\{2Q^*, 1.2Q^*\}$ and landings prices 20% below and 20% above baseline values at $t = 1$ and $t = 2$, respectively.

overage.

Figure 5d shows equilibrium harvests across regions and subperiods; A and B denote regional harvests at $t = 1$, and C and D represent regional harvests at $t = 2$. Landings are represented with their small case counterparts. In each region and in each subperiod, harvests of species 2 fish exceeds landings, i.e., $d_{2st} > 0$. Note also that with positive discards the species 2 seasonal quota lease price satisfies $\lambda_2 = p_2$. Finally, and as above, we also see that intra-regional stock differences diminish over time and both species stocks evolve toward their steady state values.

Price variation

We next consider the effects of exogenously varying economic conditions on ITQ equilibrium outcomes. We specifically focus on increasing landings prices with a fishing season. One might conjecture that equilibrium harvest behavior will induce higher harvests in periods with higher fish prices and vice versa. What is less obvious is how the temporal distribution of harvests interacts with season stock growth to determine the seasonal harvest and landings profile.

Suppose, for example, that landings prices are higher in subperiod 1. This induces higher harvests in the beginning and lower harvests in the later part of the season. A lower escapement in the first subperiod in turn reduces stocks available in later subperiods thus further reducing late-season harvests. Figure 6 shows these effects formally.

Assume stocks are symmetric across a regions at $\{x^*, x^*, x^*, x^*\}$. Figure 6a displays the seasonal equilibrium when the quotas are set symmetrically at $\{1.6Q^*, 1.6Q^*\}$ but with landings prices for both species 20% below the baseline at $t = 1$, and 20% above the baseline at $t = 2$. the expansion of the implementable sets in figure 6a highlights the amplified stock growth effects. A lower price at $t - 1$ not induces lower harvest and quota utilization, but by increasing stocks size at $t = 2$ further tilts harvests and quota utilization toward subperiod 2.

Sufficiently large variation in the price of fish throughout a season, can induce discards during subperiods of low prices. Recall that a discard requires $\lambda_i = p_{it}$. Suppose discards occur in a subperiod with $p_{it} = p_i^L = \lambda_i$. In another subperiod with $p_{it} = p_i^H > p_i^L = \lambda_i$, discards fall to zero. Figure 6b illustrates this scenario for an ecologically homogenous fishery, i.e., symmetric initial stocks at $\{x^*, x^*, x^*, x^*\}$. We assume quotas at $\{2Q^*, 1.2Q^*\}$. Finally, we let p_1 remain constant at its baseline value over the entire season, and assume p_2 varies from 20% below to 20% above its benchmark in subperiods $t = 1$ and $t = 2$, respectively.

In contrast to figure 6a, a relatively lower price for species 2 fish tilts the $t = 1$ implementable set towards species 1. The harvest of both species, 1 and 2, is lower relative to harvests at $t = 2$. Since the quota of species 2 is relatively small, it is optimal for fishermen to wait until $t = 2$ to bring species 2 harvest to the docks. At $t = 1$, much of the harvest of species 2 is discarded. This harvest overage occurs in order to avoid harvesting costs that would otherwise incur if a lower harvest of species 2 were targeted.

3.3 Comparative analysis

This section conducts comparative analyses of the effects of key model parameters on equilibrium outcomes. We continue with our simple two-species, two-region, and two-subperiods case with benchmark stock growth, dockside prices, and harvest technology (table 1). We assume the fishery is initially in steady with regional stock abundance and quotas set to their long run rent-maximizing levels. Below we will evaluate the implications of the various ecological and economic forces of our mode. The scenarios presented below have been chosen to highlight interesting and perhaps less obvious inter-species, inter-regional, and inter-temporal interactions between biological and economic components of the model.

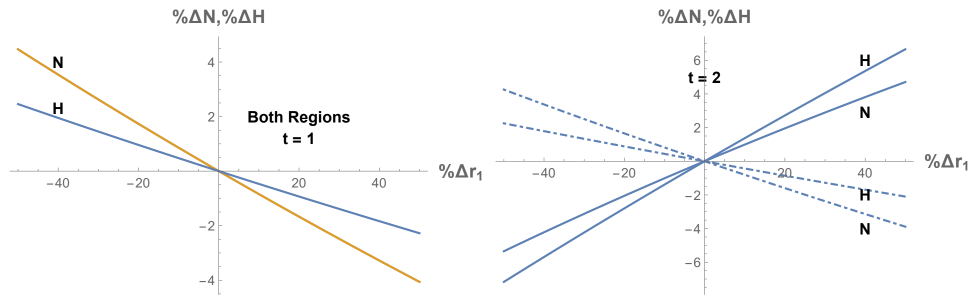
In our first experiment, we vary the intrinsic growth rates of both species stocks in region 1. The purpose is to examine spatial-temporal implications of an asymmetric ecological shock. An example, may be a pollution event that alters the quality of the marine habitat, or perhaps climate change that impacts nutrient availability in a region of the fishery.

The second experiment studies the spatial-temporal implications of inter-temporal shock to the cost of capital, e.g., a government program to subsidize new vessel capital investments (Sumaila, et al., 2010).

The first two experiments assume that the two fish species have identical characteristics within a region. In the third experiment we consider, the two regions are assumed heterogeneous with different species-specific relative abundance. We then let the price of one species vary across time. This variation impacts the two regions asymmetrically because of their differences in relative stock abundance. As a result, the equilibrium allocations vary across all three dimensions: species, regions, and time.

Regional stock growth

We let the growth rate of both species in region 1, as reflected by parameters r_{11} and r_{21}, vary from 50% below to 50% above their benchmark value of 1. All other parameters remain as reported in table 1. Figure 7a displays changes in capital deployment and harvests in subperiod 1 as regional stock growth varies along the horizontal axes, Δr_1. Figure 7b displays changes in capital and harvests in subperiod 2. The solid lines in the figure show changes in region 1 and



(a) $t = 1$ (b) $t = 2$

Figure 7: **Regional Stock Growth: Capital and Harvest Effects.** Units are reported as percentage change from benchmark model steady state values. Panel (a) results (subperiod 1) are common across regions. IN panel (b), solid lines denote region 1 and dashed lines denote region 2.

the dashed lines in regions 2. There are no difference in capital and harvests across regions in subperiod 1 and therefore only two curves are shown in figure 7a.

Consider positive growth shocks in region 1, $\Delta r_1 > 0$. Higher stock growth in region 1 implies higher stock abundance in region 1 in subperiod $t = 2$ relative to the benchmark case. It is therefore less costly and more efficient to utilize quota in region 1 at $t = 2$. Figure 7b confirms that in subperiod $t = 2$ both capital and harvest are increase in region 1 and fall in region 2.

What is striking is that, despite higher growth in region 1, both regions respond identically at subperiod $t = 1$. This should not come as a surprise though. Both regions have identical stock conditions at $t = 1$, identical dockside prices, and identical quota prices. A competitive equilibrium attracts an identical amount of capital which implies identical harvest across the two regions. That is, the quota that is reallocated from subperiod 1 to subperiod 2 is drawn from regions 1 and 2 equally.

Figure 8 show how the equilibrium quota prices change as region 1 becomes more productive. Recall that a single species-specific quota price prevails in equilibrium irrespective of where the growth occurs. Intuitively, if the fishery is more productive ($\Delta r_1 > 0$), the unit quota rent become larger reflecting the increased profitability of the fishery resource.

Capital costs

In the benchmark case the cost of capital, ρ, is common across regions and subperiods. To examine intertemporal capital price effects, we now let ρ in region 1 drop/rise by $x\%$ of its benchmark value in subperiod 1 and then rise/drop by an equal amount in subperiod 2. The capital price in region 2 is assumed to remain at its benchmark value. To focus on spatial-temporal impacts of regional capital prices, the two fish species are assumed to have identical growth characteristics. Since stocks and initial quotas are otherwise symmetric, the results presented below are common to both species.

Figures 9a and 9b show how the equilibrium capital allocation changes in region 1 and region 2, respectively, due to a seasonal and regional capital price shock. Notice that negative

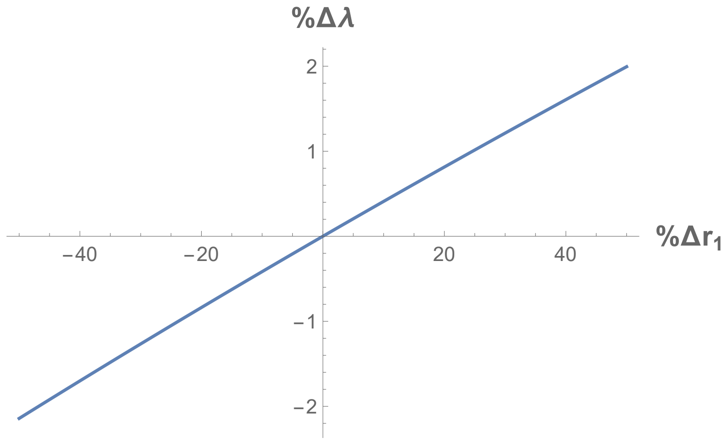
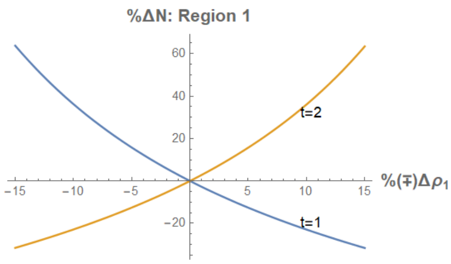


Figure 8: **Regional Stock Growth and Equilibrium Quota Prices.** Units are reported as percentage changes relative to benchmark model steady state values.

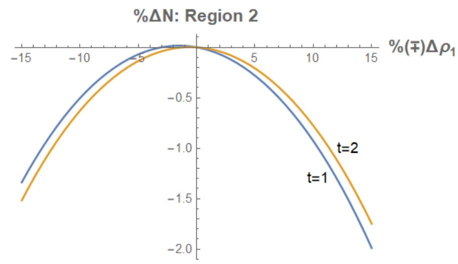
value on the horizontal axis $\mp\Delta\rho_1$ signify a lower capital price in subperiod 1 followed by the same percentage increase in the capital price in subperiod 2. Consider a rise in ρ_1 at $t = 1$ (accompanied with an offsetting fall at $t = 2$). We see that N falls at $t = 1$ in region 1. A lower harvest in region 1 implies higher stock abundance at $t = 2$, which combined with a lower cost of capital leads to a bumper rise in the capital deployment in this region at $t = 2$. The variation in the capital price does not much impact the capital deployment and harvest activity in the region 2 however (the vertical scale shows effects in the range of 0%-2%). At $t = 1$, region 2 has a relatively low cost of capital and continues to attract the quantity of capital that is close to the benchmark. At $t = 2$, a sufficiently high activity in region 1 also creates its accompanying stock effects. As a result, region 2 continues to attract about the same amount of capital as in the benchmark case.

Figure 9c displays the fishery wide and regional quota utilization at $t = 1$, with the remaining quota being utilized at $t = 2$. There is not much action in region 1. Its utilization remains close to the benchmark. Though not presented above, it is found that region 2's harvest, i.e., its quota utilization at $t = 2$ is also close to the benchmark values. Thus, the main impact of harvest activity occurs in region 1. When panels (a) and (c) of figure 9 are inspected together, it becomes clear that the aggregate harvest response is more muted in region 1 than the capital response. Thus, at $t = 1$, a fewer units of capital each harvest a larger amount than under the benchmark, whereas at $t = 2$, more units of capital harvest less per unit than under the benchmark.

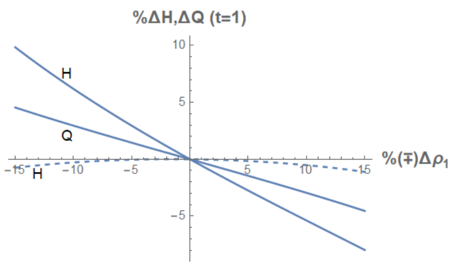
Finally, figure 9d shows changes in the equilibrium quota prices. Despite temporal changes of 15% in ρ_1, the quota price does not move beyond 1% of its benchmark value. The capital adjustments in region 1 are consistent with small change in the fishery rent. Whether ρ_1 rises in the first period and falls in the second, or vice versa does not change the direction of response of the quota price. When ρ_1 rises at $t = 1$, region 1 is more cost efficient at $t = 2$ due to lower ρ_1 and higher stocks. This raises the quota price. When ρ_1 falls at $t = 1$, much harvest activity takes place in region 1 at $t = 1$. A lower escapement however endogenously entails a



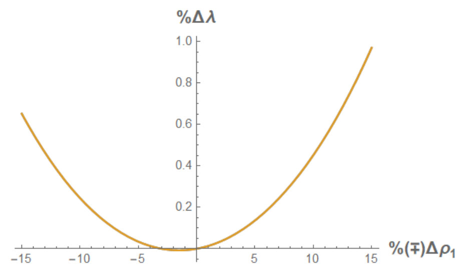
(a) Capital, region 1



(b) Capital, region 2



(c) Harvest, quota util., $t = 1$



(d) Quota price

Figure 9: **Regional-Temporal Capital Costs.** Units are reported as percentage changes relative to the benchmark model steady state values with price increases (declines) in subperiod 1 matching declines (increases) in subperiod 2.

higher growth rate. The overall impact again is an increase in the quota price.

Price changes in a heterogeneous fishery

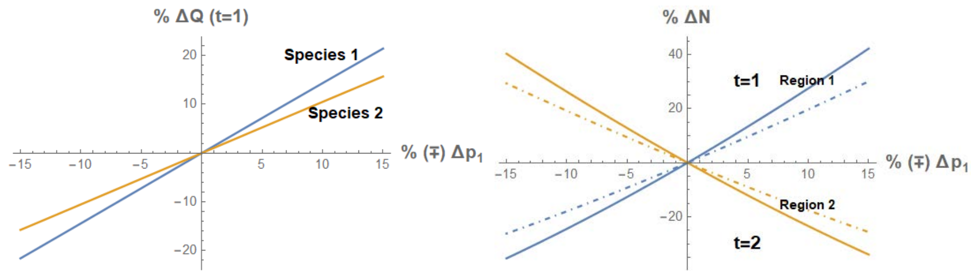
We now deviate somewhat from the above experiments and consider a fishery with regional and species-specific differences in habitat quality. We let region 1 have a higher carrying capacity for species 1, while region 2 has an identical advantage for species 2. In this modified benchmark steady state the relative stock abundance $\frac{X_{11}}{X_{21}} = \frac{X_{22}}{X_{11}} = 1.4$.

To examine region-specific, intertemporal price effects, we let the price of species 1 fall (rise) by $x\%$ in subperiod 1 and then rise (fall) by an equal amount in subperiod 2. The price change we consider is $\pm 15\%$.

We note first that the law of one price continues to hold, i.e., the landings price for either species does not vary regionally. Figure 10a shows how intertemporal price variation for species 1 impacts aggregate harvest (i.e., quota utilization) of the two species at $t = 1$ (the quota utilization at $t = 2$ is its reflection over the x-axis). Figure 10b shows changes in vessel capital deployment across regions and subperiods relative to the benchmark case.

Notice that negative values on the horizontal axis for $\mp\Delta p_1$ signify that the price of species 1 is lower in the first subperiod by the value indicated on the x-axis; the price is higher than the benchmark value by the same percentage amount in the second subperiod. The opposite is the case when this value is positive.

Figure 10b shows that a rise (fall) in the price of species 1 in the first subperiod leads



(a) (b)

Figure 10: **Landings Prices Under Regional and Species-Specific Stock Asymmetry.** Results are reported as percentage change relative to the benchmark model steady state values. Price increases (declines) in subperiod 1 match declines (increases) in subperiod 2.

to a rise (fall) in capital deployment; accompanying changes in aggregate harvest and quota utilization are shown in figure 10a. A lower price of species 1 in the first period induces fishermen to wait until the subperiod 2, not only for the higher harvest of species 1, but also for the harvest of species 2 in order to take advantage of the cost complementarities under the costly targeting technology.

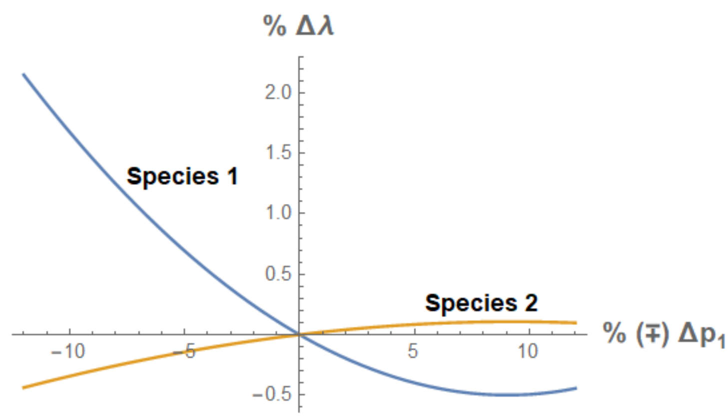


Figure 11: **Price Shock Effects: equilibrium quota prices.** Results are reported as percentage change relative to the benchmark model steady state values. Price increases (declines) in subperiod 1 match declines (increases) in subperiod 2.

The response of the equilibrium quota price is somewhat complicated. As shown in 11, a first subperiod decline in the species 1 price raises its quota price (which remains constant across the season) while the price of species 2 declines, albeit the movement in species 2 quota prices is relatively minor.

To understand this result, first recall that average prices remain the same. In the first period, stocks are identical to that under benchmark and its harvest cost advantage remains the same as under benchmark. However, a lower harvest in subperiod 1 implies higher abundance in subperiod 2 and therefore a cost advantage in the second subperiod. Stock effects decrease costs and raise unit quota value.

4 Conclusion

This paper derives a rational expectations equilibrium in a complex ecological, economic, and regulatory environment. Our model features a fairly general representation of a multiple species ecology and a joint harvesting technology. We characterize a rational recursive equilibrium for spatial-temporal harvests, landings, and discards across multiple species, quota prices, capital allocations, revenues and harvesting costs under a multiple-species quota regulation. The results demonstrate complex interactions between ecological-economic forces operational in a quota-managed fishery.

It should be noted that while we focus on a two-species, two-region and, at most, two-subperiod case of our model, the conditions for a rational recursive equilibrium extend to multiple species, regions and subperiods. Our numerical algorithm can also be applied to higher dimension problems although as is well understood, computational time increases exponentially as species, regions and seasonal subperiods increase.

Equilibrium capital allocations satisfy a condition that equates capital rent to its outside opportunity cost, and quota utilization condition in which unit quota rent is constant across space and time within a fishing season. These principles combine with the growth and spatial dispersion patterns of fish stocks to determine rational equilibrium outcomes of interest to managers. An important theme present in the model and results is that ecological and economic outcomes are determined concurrently. The implication is that marine ecosystems that support commercial fisheries are simultaneously influenced by ecological and anthropogenic (economic and regulatory) forces and should be managed as such.

We derive a mapping between initial ecological-economic conditions, regulations and equilibrium harvests, landings, discards, capital allocation outcomes, etc. Without full understanding of this mapping, well intentioned regulations will fail to meet management goals. That is, without foresight of the full range of ecological-economic consequences, setting multiple-species quotas that meet long term management goals, e.g., stock conservation and generation of rent, may be impossible. Our model can predict ecological-economic equilibrium outcomes *ex ante*, and therefore offers a powerful tool for improving quota-based fisheries management.

We have assumed that commercial fishermen are forward looking, fully rational agents that address private profit maximizing objectives within a complex ecological, economic, and regulatory environment. The rationality assumption invites some skepticism and empirical validation. On the other hand, evaluative tools that ignore the disciplining forces present in quota trading markets, and/or rely on *ad hoc* behavioral rules will lack internal validity. Our application of recursive, fully rational equilibrium methodology under realistic regulatory instrument is an important advance to implementing more holistic approaches to the management of marine ecosystems.

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6 Appendix: Proof of Proposition 1

Write the variable cost function as

$$c\left(h, \phi\left(X, H\right)\right) = \left(1 + \sum_j \gamma_j \left(\frac{h_j}{\sum_k h_k} - \frac{X_j}{\sum_k X_k}\right)^2\right) \sum_k \phi^k \left(X_k, H_k\right) h_k^\nu,$$

where j, k is the species' index. Taking its derivative with respect to h_i and then multiplying by the same h_i gets

$$\begin{aligned} c_{h_i} h_i &= \nu \left(1 + \sum_j \gamma_j \left(\frac{h_j}{\sum_k h_k} - \frac{X_j}{\sum_k X_k}\right)^2\right) \phi^i h_i^\nu \\ &\quad + 2\gamma_i \left(\frac{h_i}{\sum_k h_k} - \frac{X_i}{\sum_k X_k}\right) \left(\sum_{j \neq i} h_j\right) h_i \frac{\sum_k \phi^k \left(X_k, H_k\right) h_k^\nu}{\left(\sum_k h_k\right)^2} \\ &\quad - 2h_i \sum_{j \neq i} \gamma_j \left(\frac{h_j}{\sum_k h_k} - \frac{X_j}{\sum_k X_k}\right) h_j \frac{\sum_k \phi^i \left(X_k, H_k\right) h_k^\nu}{\left(\sum_k h_k\right)^2}. \end{aligned}$$

The last two terms equal $\frac{\sum_k \phi^i (X_k, N, H_k) h_k^\nu}{\left(\sum_k h_k\right)^2}$ times

$$\begin{aligned} \Lambda_i &\equiv 2\gamma_i \left(\frac{h_i}{\sum_k h_k} - \frac{X_i}{\sum_k X_k}\right) \left(\sum_{j \neq i} h_j\right) h_i - 2h_i \sum_{j \neq i} \gamma_j \left(\frac{h_j}{\sum_k h_k} - \frac{X_j}{\sum_k X_k}\right) h_j \\ &= 2h_i \gamma_i \left(\frac{h_i}{\sum_k h_k} - \frac{X_i}{\sum_k X_k}\right) \left(\sum_j h_j\right) - 2h_i \sum_j \gamma_j h_j \left(\frac{h_j}{\sum_k h_k} - \frac{X_j}{\sum_k X_k}\right). \end{aligned}$$

Note that

$$\begin{aligned}\sum_{\iota}\Lambda_i &= 2\left(\sum_j h_j\right)\sum_i h_i\gamma_i\left(\frac{h_i}{\sum_k h_k}-\frac{X_i}{\sum_k X_k}\right)\\ &\quad -2\left(\sum_i h_i\right)\sum_j \gamma_j h_j\left(\frac{h_j}{\sum_k h_k}-\frac{X_j}{\sum_k X_k}\right)\\ &= 0.\end{aligned}$$

Therefore,

$$\begin{aligned}\sum_{\iota} c_{h_i}h_i &= \nu\left(1+\sum_j \gamma_j\left(\frac{h_j}{\sum_k h_k}-\frac{X_j}{\sum_k X_k}\right)^2\right)\sum_{\iota}\phi^i h_i^{\nu}\\ &\quad +\frac{\sum_k \phi^i\left(X_k,H_k\right)h_k^{\nu}}{\left(\sum_k h_k\right)^2}\sum_{\iota}\Lambda_i\\ &= \nu c\left(h,\phi\left(X,H\right)\right).\end{aligned}$$

Suppose, instead, that the cost function takes the following form:

$$c\left(h,\phi\left(X,H\right)\right)=\sum_j\left(1+\gamma_j\left(\frac{h_j}{\sum_k h_k}-\frac{X_j}{\sum_k X_k}\right)^2\right)\phi^j\left(X_j,H_j\right)h_j^{\nu}$$

In this case,

$$\begin{aligned}c_{h_i}h_i &= \nu\left(1+\gamma_i\left(\frac{h_i}{\sum_k h_k}-\frac{X_i}{\sum_k X_k}\right)^2\right)\phi^i h_i^{\nu}\\ &\quad +2\gamma_i\left(\frac{h_i}{\sum_k h_k}-\frac{X_i}{\sum_k X_k}\right)\frac{h_i}{\left(\sum_k h_k\right)^2}\left(\sum_{j\neq i}h_j\right)\phi^i h_i^{\nu}\\ &\quad -2h_i\sum_{j\neq i}\gamma_j\left(\frac{h_j}{\sum_k h_k}-\frac{X_j}{\sum_k X_k}\right)\frac{h_j}{\left(\sum_k h_k\right)^2}\phi^j h_j^{\nu}.\end{aligned}$$

The last two terms equal $\frac{1}{\left(\sum_k h_k\right)^2}$ times

$$\begin{aligned}\Xi_i &\equiv 2\left(\sum_j h_j\right)\left(\gamma_i h_i\left(\frac{h_i}{\sum_k h_k}-\frac{X_i}{\sum_k X_k}\right)\phi^i h_i^{\nu}\right)\\ &\quad -2h_i\sum_j \gamma_j h_j\left(\frac{h_j}{\sum_k h_k}-\frac{X_j}{\sum_k X_k}\right)h_j\phi^j h_j^{\nu}.\end{aligned}$$

Once again,

$$\begin{aligned}\sum_{\iota} \Xi_i &= 2\left(\sum_j h_j\right)\sum_i \gamma_i h_i \left(\frac{h_i}{\sum_k h_k} - \frac{X_i}{\sum_k X_k}\right) \\ &\quad -2\left(\sum_i h_i\right)\sum_j \gamma_j h_j \left(\frac{h_j}{\sum_k h_k} - \frac{X_j}{\sum_k X_k}\right) \\ &= 0,\end{aligned}$$

which, once again, implies

$$\sum_{\iota} c_{h_i} h_i = \nu c\left(h, \phi\left(X, H\right)\right).$$

7 Appendix: Computational Algorithm

The equilibrium allocations for $T \geq 2$ are obtained numerically by following the steps enumerated below. We continue to focus on a fishery with two regions 1 and 2.

1. Fix $X \equiv \{X_{11}, X_{21}, X_{12}, X_{22}\}$. Given X, generate regional and aggregate implementable partitions by following the steps discussed in section 3.1.

2. Given these implementability partitions, compute

$$\{N \equiv \{N_1, N_2\}, H \equiv \{H_{11}, H_{21}, H_{12}, H_{22}\}, \{\lambda_1, \lambda_2\}\}$$

   for all possible $Q \equiv \{Q_1, Q_2\}$.

3. Repeat step 2 over a plausible domain for X. These computations also obtain the multiplier values for $\lambda_i\left(X, Q\right) \in [0, p_i]$.

4. Now consider subperiod $T-1$ and T. The optimal solution to the static problem in any period given $\{X, Q\}$ has already been solved. Let $\{X, Q\}$ be the state in subperiod $T-1$. But now the optimal choice problem entails *only a part of Q to be utilized* and the remaining to be carried forward to T. Let Q' be carried over to T. Then optimal static choice problem in $T-1$ gets $\lambda_i\left(X, Q-Q'\right)$ and $\{N, H\}$ for $T-1$ as functions of $\{X, Q-Q'\}$. In Equilibrium $X' = \Gamma\left(X-H\right)$. Then in T, $\lambda_i\left(\Gamma\left(X-H\right), Q'\right)$. The equilibrium requires that

$$\lambda_i\left(X, Q-Q'\right) = \lambda_i\left(\Gamma\left(X - H\left(X, Q\right)\right), Q'\right)$$

   Solving this fixed point problem recursively obtains season's optimal quota utilization over multiple subperiods.