

FISHERY MANAGEMENT WHEN BIOLOGICAL AND ECONOMIC DISTURBANCES ARE CORRELATED.

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ABSTRACT

Economists studying the management of fisheries have universally assumed disturbances affecting harvest costs are unrelated to disturbances affecting biological growth. This paper gives examples of commercially valuable species that are impacted reproductively and behaviorally by a single environmental variable (e.g., temperature), leading to correlated disturbances in current marginal harvest costs and future biological growth. A general analytical model examines the importance of considering correlated disturbances when choosing optimal escapement targets, and shows how the presence of correlation affects the value of waiting for information on harvest costs. These results give insight as to the appropriate use of “self-correcting” mechanisms for controlling harvest, such as landing fees, versus hard targets, and provide a framework for proactive management of fisheries in the face of large-scale marine disturbances that can affect both the biological growth and behavior of commercially valuable species.

Keywords: fishery, correlated uncertainty, environmental variability, optimal management

INTRODUCTION

Recent research has documented the precarious condition of many of the world’s fisheries (Jackson, 2008; Worm et al., 2009). As of 2007, 52% of global marine fish stocks were classified as fully exploited, 19% over-exploited, and 8% depleted. Additionally, seven of the top ten species by landings – representing 30% of total global take – were fully exploited, implying that as worldwide demand for fish expands, a wider range of species will likely experience severe fishing pressure (FAO, 2009a).

One of the most significant obstacles to management success in marine fisheries is biological and environmental uncertainty (Roughgarden & Smith, 1996). This paper considers two, environment-driven sources of stochasticity: variability in biological growth and variability in catchability. The latter refers to a disturbance to the processes relating escapement from the current fishing period to available biomass in the next fishing period. Variability in catchability is assumed to affect the marginal cost of harvesting fish in the current period. The analysis is presented in a discrete-time framework in which the current period stock is known with certainty, marginal harvest costs are stochastic, and escapement is subject to stochastic biological growth, implying the biomass available next period is uncertain. The random elements are potentially correlated with each other in each fishing period. To justify this potential, specific examples are presented in which there is evidence that a single, ecosystem-scale environmental variable can have impacts on both the catchability and growth of valuable species, leading to correlated errors in the empirical relationships describing production and biomass growth. This is a novel extension within the fisheries economics literature, where researchers have universally assumed independence between stochastic elements.

Under the assumption of correlated cost and growth disturbances, the question of optimal escapement in a fishery is examined in the spirit of Reed (1979). Two decision-makers are considered: a regulator who must choose escapement targets before the realization of true harvest costs, and a sole owner who may adjust escapement targets based on the realization costs that, in turn, act as a forecast of future growth. It is shown that the value of waiting for information about costs before designating escapement targets is affected by correlation, and that flexibility in setting targets – often difficult to justify politically – may not be particularly valuable in certain fisheries. This latter discussion offers insight as to the appropriateness of different decentralized harvest control mechanisms (HCMs) (e.g., ITQs, ITEs, landing fees) in the presence of correlation. Although brevity precludes the formal exposition of these results, intuition is achieved relatively easily by considering firm-level responses to various HCMs.

Finally, we discuss the broader implications of this analysis for the study of large-scale marine disturbances. Anecdotal evidence suggests in some fisheries, disturbances that negatively affect a species’ biological reproduction and growth also elicit a behavioral response in the species that is subsequently exploited by commercial fishing operations, leading to hyper-stable catch per unit effort (CPUE) as biomass declines. In other words, a disturbance that causes lower-than-expected growth and higher-than-expected catch efficiency for a given level of biomass. The health of these fisheries depends on understanding environment-biological links, and the inclusion of predictive

models in the management process. The remainder of this paper proceeds as follows. First, evidence of correlated uncertainty in various fisheries is presented. The relevant literature on optimal harvest in a fishery is then reviewed, followed by a description of the analytical model. Results, conclusions, and implications are then discussed.

EXAMPLES OF CORRELATED DEVIATIONS IN FISHERIES

Evidence from the Georgia blue crab fishery

In Georgia, USA, the blue crab (*Callinectes sapidus*) is the second most valuable commercial fishery. There are about 80 small, independently owned operations focused on the trade of live crabs (Evans, 1998). It has been estimated that 70% of year-to-year variability in blue crab stocks is due to changes in the ambient environment, the most important component being river discharge (Rogers, Arredondo, & Latham, 1990). When river flow drops, salinity increases, contributing to the proliferation of a blood parasite, *Hematodinium*, that causes suffocation in crabs and spreads rapidly in high temperature, high salinity environments (Messick, Jordan, & Van Heukelem, 1999). Low river flow is also associated with decreased recruitment of juveniles. Juvenile crabs are more sensitive to salinity than adults, and as river discharge declines, their effective habitat becomes smaller, leading to an increase in mortality due to predation (Wilber, 1994; Wrona, 2004). River flow also affects the distribution of the adult stock. Adult blue crabs are found predominantly in moderately saline waters (15 to 18 ppt; ocean salinity is ~35 ppt)¹. Research has suggested this may result from changes in prey distribution (e.g., juveniles), which are more sensitive to salinity, or predation from marine predators (Wrona, 2004). In any case, when river flow declines, the salinity gradient in estuaries expands upstream into narrow tributaries, and crabs migrate towards these areas, congregating into denser aggregations based on coastal geomorphology. Crabbers are aware of movement patterns, and will alter trap placements based on observed river flow². In other words, it appears that decreased river flow could lead to situations where the stock-adjusted efficiency of gear – or “catchability” – increases. This is anecdotal, however, and so it helps to present some simple statistical results supporting the claims above.

To determine how river flow affects the Georgia blue crab fishery, stock assessment and commercial harvest data from the Georgia Department of Natural Resources³ and river flow data from USGS are used to estimate a monthly harvest production function and a month-to-month stock transition equation. The choice of monthly transitions allows accounting for the relatively rapid behavioral response of crabs to river discharge – traversing the salinity gradient – and also provides a focus consistent with the theme of this paper: environmental disturbances that occur on a short enough time scale so that inter-period adjustment of harvest targets are difficult to implement. The analysis focuses on the high season for crabbing each year, which occurs between May and November and has historically contributed about 80% of total yearly harvests. The winter crabbing industry is fundamentally different from that in the summer; crabs are inactive and most activities are focused on the lower estuary where females relocate in preparation for spring spawning. Additionally, juveniles cease their molting process, and any impact of river flow on those juveniles’ entrance to the adult population is unobservable (Wrona, 2004).

Georgia has conducted fishery-independent biomass surveys for the blue crab fishery since 1976. The surveys focus on six “sounds,” or estuarine systems (of approximately 10 that are fished intensively), each of which is sampled six times monthly in three different broad locations (continental shelf, lower sound, and upper sound). Of these six, three are fed by major rivers: Ossabaw Sound, fed by the Ogeechee River; St. Andrew’s Sound, fed by the Satilla River; and, Cumberland/St. Marys Sound, fed by St. Marys River (see Figure 1). The analysis focuses on these three sounds, which have accounted for 32% of all harvests between 1989 and 2009 and 37% since 2000. Two quasi-structural equations are estimated. It is assumed fishery production occurs via Cobb-Douglas technology with additional terms that account for variability in river flow and month- and sound-specific fixed effects

$$h_{m,s} = q * tr_{m,s}^{\alpha_0} * X_{m,s}^{\alpha_1} * A * e^{\epsilon_h}$$

where q is the harvest technology, or “catchability coefficient,” $tr_{m,s}$ is the number of trips made in a particular month in a particular sound, $X_{m,s}$ is a biomass index, ϵ is a normally distributed error term, and A is a vector of river flow-related variables and dummy variables for the month and location of harvests. Variables included to evaluate the impact of freshwater flow include dummy variables indicating a 50% or 75% directional deviation in local flow from the monthly mean over the estimation period and various transformations of the continuous flow variable. The second equation represents the evolution of biomass during the fishing season

$$X_{m+1,s} = (X_{m,s} + Juv_{m,s} - h_{m,s})^{\beta_0} * B * e^{\epsilon_x}$$

where $Juv_{m,s}$ is an index of juvenile crabs close to adult classification as generated by survey trawls and $(X_{m,s} + Juv_{m,s} - h_{m,s})$ represents an index of escapement. β_0 is the rate at which escapement evolves into the next-period stock, and B is the analog to A in the production function equation. These two equations can be transformed for estimation via least squares by taking the natural log of each side, and estimated independently to determine the biological and economic parameters of the model. Table 1 displays the results of the limited models, in which variables were removed based on a backwards, stepwise regression process.



Figure 1. Map of the Georgia Coast. Courtesy of VJ Henry, The New Georgia Encyclopedia.

Harvest production			Stock transition		
Parameter	Coefficient	T ratio	Parameter	Coefficient	T ratio
q	1982.1	28.43	Constant	-0.6750	3.18
α_2	0.6418	13.66	β_2	0.5108	16.72
α_1	0.1459	7.61	lnFlowRatio	0.1481	4.01
lnFlowRatio	-0.0557	2.68	Dum (Jun)	0.4865	3.17
Dum (Jul)	0.1852	2.54	Dum (Aug)	0.8121	5.40
Dum (Aug)	0.3497	3.85	Dum (Sep)	1.0418	6.75
Dum (Sep)	0.2551	2.73	Dum (Oct)	0.9194	6.02
Dum (Oct)	0.2450	5.23	Dum (Nov)	0.6934	5.23
Dum (St. Marys)	-0.2985	4.34			
Obs.	423		Obs.	420	
F-stat	44.23		F-stat	90.21	
r^2	0.663		r^2	0.43	

Table 1. GLS estimation results. Breusch-Pagan and White's tests confirmed presence of heteroskedasticity; robust standard errors are reported.

The flow variable of interest is the log of the ratio of current flows to the long-term monthly average. This variable is significant in both equations. For the harvest production function, a one percent increase in river flow over its average acts to decrease harvests by approximately 0.056%. In the stock transition equation, a one percent increase in river flow over the average leads to an increase in the next month's biomass index of approximately 0.14%. The magnitude of these coefficients appears small, but considering the highly variable nature of coastal river flow in Georgia (see Table 2), it is clear significant impacts could be observed.

River	Mean flow (ft ³ /s)	St. Dev.	Min	Max	Obs
Ogeechee	1207	1361	91.2	7579	145
Satilla	1175	1857	25.4	10490	145
St. Marys	493	859	12.9	6569	145

Table 2. Summary statistics for the three rivers included in the analysis. Flow statistics are for the period May-November, 1989-2009.

River flow is associated with lower than expected harvests in the current month and higher than expected stock in the next month, although the more appropriate manner to frame this explanation is in regard to lower flow, as drought and urbanization have led to consistently low flows in the past decade (Harper, 2010). The analysis here implies that periods of low river flow are associated with higher harvests than what would be expected under a traditional, biomass-density-dependent harvest assumption. Consider the case when river flow has dropped by 50%. We would expect harvests this period to increase by approximately 2.5%. At the same time, biomass in the next period is expected to be about 7.4% lower than it would have been following an average flow month. This type of relationship might have played a role in the collapse of the crab fishery earlier this decade by breaking down the density-dependence of CPUE (Lee & Frischer, 2004).

The analysis here is presented generally, so it is prudent to discuss whether correlation exists in other fisheries. As shown below, these types of relationships – an environmental variable driving correlated deviations in both the cost of fishing and biological growth or reproduction – are likely important for other commercially valuable species.

The Atlantic horse mackerel and sea-surface temperature

The north-Atlantic horse mackerel (*Trachurus trachurus*) is a temperate species found in the north-east Atlantic. The fishery is prosecuted by European trawlers and purse-seiners (Abaunza et al., 2003), and supported landings of 204,935 metric tons in 2007 (FAO, 2009b). Catch management has been enforced in some areas, but a large component of the fishery – the “western stock” – remains unregulated. Catch limits were recently proposed for the western stock by the European Union (EU, 2009). Lavin, et al. (2007) found that sea surface temperature (SST) and a wind variable (both driven by the North Atlantic Oscillation) explained over 65% of recruitment variability of the Atlantic horse mackerel. Summers with cooler SST are correlated with higher recruitment the following year, likely due to temperature-sensitivity of eggs and larvae. Higher SST induces horse mackerel to spawn earlier than the normal range of May to July, leading to increased exposure of eggs to mid- and late-summer temperatures, and increased pelagic transport of larvae leading to higher mortality from predation, etc. At the same time, Iversen, Skogen, and Svendsen, (2002) found higher SST to be associated with a greater influx of Atlantic waters to the North Sea, with harvests and CPUE six months later positively and strongly associated with that influx. Essentially, the influx of warm Atlantic waters promotes primary production, increasing schooling behavior and making fish more susceptible to gear. The consistency of the influx-harvest association has led to the Norwegian fleet using influx data to help make harvest projections. Reid, Fatima, & Svendsen, (2001) found harvest variability in the afore-mentioned western stock matches the pattern in the North Sea, implying that catches outside of the North Sea are potentially influenced by the same environmental trends. Both recruitment and catch efficiency for the horse mackerel are influenced by prevailing climate regimes in the north-east Atlantic. The evidence shows warmer temperatures lead to an increase in near-term CPUE and a decrease in recruitment to future year classes.

Tropical Pacific tunas and ENSO

The Pacific Ocean supplied 65% of global tuna catches in 2007, with the most commonly exploited species being albacore, bigeye, skipjack, and yellowfin (WCPFC, 2008a). The size of the Pacific makes management incredibly complicated; it is nearly impossible to measure abundance directly, and coordination of international fleets around a common set of objectives has been difficult. In the western Pacific, tuna stocks have been managed since 2004 by The Western and Central Pacific Fisheries Commission (WCPFC). Yellowfin (fished at capacity) and bigeye

(overfished) are subject to active management (WCPFC, 2008b), meaning that purse-seine fishing vessels targeting these two species are prohibited from using fish aggregation devices, and are subject to a “vessel-day scheme” that implements an total fishing days quota and assigns tradable, bankable rights to fleets. The albacore has been subject to a moratorium on new capacity since 2005 (WCPFC, 2005; WCPFC, 2006). There are no significant limitations on skipjack, a fast-growing species that made up the majority of total catches in 2007 (WCPFC, 2008a).

Lehodey (2000) investigated the impact of the El Niño Southern Oscillation (ENSO) on Pacific tuna populations and found evidence that El Niño and La Niña⁴ events can have significant direct (contemporaneous) impacts on CPUE by affecting catchability and indirect (lagged) impacts on CPUE through changes in biomass. The direct effect is negative for skipjack and albacore and positive for bigeye and yellowfin. The primary habitat of skipjack is the western Pacific warm pool, which extends and shifts during these events resulting in a more scattered distribution. The results for albacore are not as robust, but it is proposed that migration from traditional fishing grounds drives drops in current-period CPUE. The positive impact on bigeye and yellowfin CPUE is due to a vertical (through the water column) extension of habitable range, increasing the availability of the fish to purse seine and hook-and-line gear (Hampton, Begelow, & Labelle, 1998; Lehodey, 2000). At the same time, El Niño events have a positive impact on skipjack, bigeye, and yellowfin recruitment and a negative impact on albacore recruitment in the western Pacific. For skipjack, this positive recruitment effect is deduced from lagged stock effect on CPUE occurring 6-12 months later. For bigeye, yellowfin, and albacore, this effect is weaker and occurs at periods >14 months⁵. Although there is significant variation in these results the general trend is that both current period CPUE and future recruitment are impacted by prevailing ENSO patterns.

Table 3 summarizes the relationships for the six species investigated thus far. Two effects are distilled from the discussion above: impacts on current-period CPUE (i.e., catchability or marginal harvest costs) and impacts on next-period biomass. The “next-period” differs in duration for each species. For instance, for blue crabs this period is approximately one month, as indicated by the empirical analysis. For tunas, the period is more clearly spelled out in the discussion of lagged recruitment effects by Lehodey. As the relationships presented here are, for the most part, based on conjecture, they are displayed qualitatively.

Species	Driver	Effect of driver on		Correlation (CPUE-Growth)	Correlation (Cost-Growth)
		CPUE	Biomass growth		
Blue crab	Decreased river discharge	+	—	—	+
H. mackerel	SST	+	—	—	+
Albacore	El Niño	—	—	+	—
Bigeye	El Niño	+	+	+	—
Skipjack	El Niño	—	+	—	+
Yellowfin	El Niño	+	+	+	—

Table 3. Qualitative description of correlation between biomass growth and CPUE.

These examples are not exhaustive, but represent a range of species that are important to both commercial fleets and small-scale, coastal communities. In the conclusions, additional examples are discussed.

RELATED LITERATURE

A number of papers have studied the question of how to optimally harvest a renewable resource under uncertainty. Beginning with Reed (1979), authors have analyzed the effect of stochastic growth on optimal escapement (Clark & Kirkwood, 1986; Costello & Polasky, 2008; Costello, Polasky, & Solow, 2001; Sethi, et al., 2005). Reed’s original analysis ultimately prescribed a rule of “constant escapement.” In essence, the stock of fish only affects the harvest in any given period through the difference between that stock level and the time-independent optimal escapement. Roughgarden and Smith (1996) discuss the implications of three types of uncertainty – stochastic biological growth, inaccurate stock assessments, and imprecise harvest implementation⁶ – and make the case for managing a fishery for ecological stability rather than sustainable yield. Extending this result, Sethi, et al. (2005), present a formalized numerical analysis and find a number of results. Reed’s constant escapement policy is appropriate when uncertainty is low, or when there is uncertainty in growth or harvest implementation. Large uncertainty in stock measurement has a different impact, resulting in rejection of the constant escapement rule in favor of a state-dependent policy. Random elements are independently distributed, and it is difficult to determine if this qualitatively affects results.

Costello, Polasky, and Solow (2001) consider only biological uncertainty, but their analysis is still similar to that presented here. They extend Reed's model to allow for the imprecise prediction of environmental conditions affecting future biological growth and develop analytical solutions to a set general questions. They find that the prediction of adverse biological growth leads to a lower optimal escapement in the current period. In the absence of serially correlated shocks, forecasts beyond the next period are not valuable. This result follows directly the notion of a "state-independent" optimal control mentioned above: as in Reed, the dynamic optimization problem can be broken down into a series of single-period problems in which current harvest value is weighed against potential growth in the next period. Their research is similar that presented here because of the presence of an environmental variable that helps predict future growth. In this paper, the observation of harvest costs acts in a similar way, relaying information about future growth conditions through the mechanism of correlation.

The possibility that cost and biological growth disturbances in a fishery are correlated has never been analyzed by economists. Analytically, this is convenient; a non-zero covariance term can confuse results if the goal is not concerned with correlation. For instance, Sethi, et al. (2005) assume no correlation between stochastic elements, and note "In principle, one could include non-zero covariance between variables of each type. We do not explore correlated uncertainty of that type here." In other papers it appears that the assumption of independence is relaxed. This is either an artifact of algebraic manipulation (Anderson, 1986; Koenig, 1984) or considered in response to unexpected results, with no contextual justification (Androkovich & Stollery, 1991). Correlated disturbances have been considered in the pollution control literature (Shrestha, 2001), however, those papers have focused only on the choice between different mechanisms of control such as taxes or tradable quotas. This paper offers a new approach to the problem, and presents additional insights as to the importance of decision timing and management structure.

THE MODEL

The model used is a discrete-time, single species model of a fishery. Uncertainty enters the problem in two forms: a shock to current costs and stochastic growth of escapement at the end of the fishing period. The goal is to maximize an infinite stream of profits from the fishery. At the beginning of each period $t = 1, 2, \dots, \infty$, the stock of fish x_t is observed by all actors with certainty. Harvests h_t remove biomass from the fishery, and the resulting escapement e_t is subject to the Markovian stock transition equation

$$x_{t+1} = g(e_t, \theta_t) \quad (1)$$

where biomass growth, $g(e_t, \theta_t)$, is increasing and concave in escapement, e_t , and increasing in θ_t , a random variable representing environmental perturbations. θ_t is defined by the conditional cumulative distribution function $F(\theta; \eta)$, bounded over the support $[a, b]$. The demand for fish is assumed perfectly elastic at price p per unit. The marginal cost of fishing is represented by $\eta_t c(s)$ and is a non-increasing function of the instantaneous stock during the fishing period, where η_t is a random, shock to marginal harvest costs with an expected value of one and binary outcomes (η^h, η^l) representing high and low costs⁷. Total costs incurred while fishing the beginning stock, x_t , down to a level of escapement, e_t , are represented by $\int_{e_t}^{x_t} \eta_t c(s) ds$. Using the identity $h_t = x_t - e_t$, the objective function for the regulator is written in terms of escapement

$$V_t(x_t) = \max_{e_t} E_t \left\{ \sum_{t=1}^{\infty} \delta^{t-1} \left[p(x_t - e_t) - \int_{e_t}^{x_t} \eta_t c(s) ds \right] \right\} \quad (2)$$

subject to (1), and where $\delta = \frac{1}{1+r}$ and r is the discount rate. The decision process occurs as follows: 1) The stock is observed with certainty by the regulator/owner and fishermen; 2) The regulator chooses a harvest control mechanism and implementation level⁸; 3) Fishing commences and the cost shock is observed by fishermen; 4) Fishing ends, harvests are observed, and escapement is subject to (1); and, 5) Growth from step 4 becomes the stock in period $t + 1$, and steps 1 – 4 are repeated.

Two management structures are evaluated: a sole owner who is able to observe the stock and cost shock before making harvest decisions, and a regulator who must choose escapement before the cost shock is observed⁹.

The sole owner

The sole owner is able to adjust harvest targets *after* the cost shock is realized, effectively removing one element of uncertainty. Rewriting (2) as a stochastic, dynamic optimization problem yields

$$V_t^s(x_t) = \max_{e_t} p(x_t - e_t) - \int_{e_t}^{x_t} \eta_t c(s) ds + \delta E_{t,\eta_t} [V_{t+1}^s(x_{t+1})] \quad (3)$$

where superscripts indicate the management structure being analyzed. For an interior solution, e_t^* , to exist, the following necessary condition must be satisfied

$$-p + \eta_t c(e_t^*) + \delta E_{t,\eta_t} \left[\frac{\partial V_{t+1}^s(x_{t+1})}{\partial x_{t+1}} \frac{\partial x_{t+1}}{\partial e_t^*} \right] = 0 \quad (4)$$

(3) is strictly concave in escapement¹⁰, a sufficient condition for the interior solution depicted by (4) to be a maximum. Under perfectly elastic demand and harvest-independent marginal costs, the marginal current period profit and future value – the components of (4) – are affected only by the choice of escapement, not the level of harvests. These types of problems can be solved analytically because the dynamic programming problem is instead replaced by a series of single-period optimization problem; all value associated with $V_{t+1}^s(x_{t+1})$ is attributed to the immediate harvest value in period $t + 1$. With this understanding, rewriting (3) and (4) yields

$$V_t^s(x_t) = \max_{e_t} p(x_t - e_t) - \int_{e_t}^{x_t} \eta_t c(s) ds + \delta E_t \left[p(g(e_t^*, \theta_t) - \tilde{e}) - \int_{\tilde{e}}^{g(e_t^*, \theta_t)} \eta_{t+1} c(s) ds \right] \quad (5)$$

and

$$-p + \eta_t c(e_t^*) + \delta E_t \left[g_e(e_t^*, \theta_t) (p - \eta_{t+1} c(g(e_t^*, \theta_t))) \right] = 0 \quad (6)$$

where g_e is the partial derivative of the growth function with respect to escapement and \tilde{e} is some lower bound on escapement representing, for instance, the zero profit condition. We can now investigate how the realization of η_t and the relaxation of the assumption of independence between η_t and θ_t affects escapement decisions for the sole owner. Consider the following three alternatives regarding the relationship between η and θ :

Case 1: $F_\eta(\theta; \eta) = 0$ in the sense of first-order stochastic dominance¹¹. η and θ are uncorrelated.

Case 2: $F_\eta(\theta; \eta) < 0$ in the sense of first-order stochastic dominance. η and θ are positively correlated.

Case 3: $F_\eta(\theta; \eta) > 0$ in the sense of first-order stochastic dominance. η and θ are negatively correlated.

Proposition 1. When the growth shock is multiplicative, a positive (negative) cost shock will increase (decrease) the optimal escapement e_t^* under Case 1 and Case 2. Under Case 3, the results are ambiguous.

Proof: Recognizing that the expected value of η_{t+1} is one, (6) can be rewritten

$$-p + \eta_t c(e_t^*) + \delta \int_a^b g_e(e_t^*, \theta) (p - c(g(e_t^*, \theta))) dF(\theta; \eta) = 0 \quad (7)$$

Fully differentiating (7) with respect to e_t and η_t (see appendix for procedure) generates

$$\frac{de_t^*}{d\eta_t} = \frac{-c(e_t^*) + \delta \int_a^b \overbrace{(g_{e\theta}(e_t^*, \theta) (p - c(g(e_t^*, \theta))) - g_e g_\theta c')}^? F_\eta(\theta; \eta) d\theta}{\underbrace{SOSC}_-} \quad (8)$$

The denominator of (8) is the second order sufficient condition for a maximum of (3). The first term of the numerator is the direct effect of a cost shock – the impact on current-period profits. The second term is the indirect effect of observing the cost shock on the expectation of future growth. That term is ambiguous for a general growth function, but Insight can be gained by defining the functional placement of θ_t . Consider a multiplicative shock as proposed by Reed (1979) such that (1) becomes $g(e_t, \theta_t) = \theta_t g(e_t)$ with supports on the distribution for θ_t bounded such that $0 < a < 1 < b < \infty$ and $E[\theta_t] = 1$. Dropping interior arguments for succinctness, (8) becomes

$$\frac{de_t^*}{d\eta_t} = \frac{-c + \delta \int_a^b \overbrace{(g_e(p - c(\cdot)) - \theta g(e_t^*) c')}^+ F_\eta(\theta; \eta) d\theta}{\underbrace{SOSC}_-} \quad (9)$$

The second term in the numerator of (9) has the same sign as $F_\eta(\theta; \eta)$ ¹². For Case 1, $F_\eta(\theta; \eta) = 0$; only the direct effect of a cost shock (the first term in the numerator) is considered. A positive marginal cost of fishing implies that a positive cost shock will increase optimal escapement. In Case 2, a positive cost shock is correlated with a higher

expectation for growth and therefore optimal escapement increases even further than under no correlation. For Case 3 (negative correlation), it is possible that optimal escapement could decrease depending on the magnitude of the cost and growth shocks, the slope of the marginal cost curve, c' , and the slope of the growth function. This result might seem counter-intuitive; biologically, it seems prudent to *increase* escapement when you expect growth to be lower. In this specification, however, with a compensating growth function, the only the fishery can collapse is for harvests to exhaust available stock in a given period. Economic return is the only consideration, and escapement is seen as an investment, the growth of which is determined by biological parameters and the discount rate.

Proposition 2. When the growth shock is additive with escapement, a positive (negative) cost shock will increase (decrease) the optimal escapement under Case 1. Under Cases 2 and 3 the results are ambiguous. The effect of a positive cost shock on optimal escapement will depend on the slope of the marginal cost function and the second derivative of the growth function.

Proof: Consider an additive shock to escapement so that (1) is expressed as $g(e_t, \theta_t) = g(e_t + \theta_t)$ with supports on the distribution for θ_t bounded such that $a < 0 < b$ and $E[\theta_t] = 0$. This shock could be interpreted as a change in mortality of escapement due to environmental conditions. In this case, (8) becomes

$$\frac{de_t^*}{d\eta_t} = \frac{\overbrace{-c + \delta \int_a^b (g_{ee}(p - c) - (g_e)^2 c') F_\eta(\theta; \eta) d\theta}^?}{\underbrace{SOSC}_-} \quad (10)$$

The term preceding $F_\eta(\theta; \eta)$ is now ambiguous. Curvature in the growth function implies that when growth is expected to be lower than average, the marginal influence of escapement on future biomass levels increases. In effect, escapement acts to “replace” biomass lost due to the negative shock. The effect of curvature in the cost function (the second term in the integral) is of the same sign as (9); the relative strength of these two terms must be weighed to sign the indirect effect of a cost shock and the sum of the direct and indirect effects.

Propositions 1 and 2 highlight the sensitivity of results to the structural specification of the growth shock and growth function. Clearly, there are other structural assumptions that can be imposed that would lead to different signings of the indirect effect of the cost shock. To clarify, two definitions associated with the unknown term in (8) are given:

Definition 1: If $g_{e\theta}(p - c) - g_e g_\theta c' > 0$, return-on-investment (**ROI**) incentives dominate the indirect effect.

Definition 2: If $g_{e\theta}(p - c) - g_e g_\theta c' < 0$, replacement incentives dominate the indirect effect.

ROI incentives follow from the logic that, if poor growth is expected, then the return on escapement is likewise expected to be poor and harvests this period increase in relative value. This result mirrors that of Costello, Polasky, and Solow (2001), who show that forecasts of lower growth should decrease optimal escapement this period¹³. Replacement incentives, on the other hand, imply that a negative shock to growth is associated with an increase in the marginal value of escapement. As shown in Proposition 2, a growth shock that enters additively with escapement could lead to replacement incentives. Other intuitive reasons for replacement incentives to dominate could include risk of extinction or a desire to maintain a specific biomass target for biological, economic, or political reasons¹⁴.

In an effort to aggregate and clarify the analytical results, Table 2 shows the eight possible combinations of the direction of the cost shock, the type of incentive associated with escapement, and the direction of correlation.

Example	Cost Shock	Correlation	ROI or replacement	Optimal escapement
1	+	+	ROI	+
2	+	—	ROI	?
3	+	+	Replacement	?
4	+	—	Replacement	+
5	—	+	ROI	—
6	—	—	ROI	?
7	—	+	Replacement	?
8	—	—	Replacement	—

Table 4. The effect of correlation on optimal escapement.

The regulator

Unlike the sole owner, the regulator must set harvest targets before realization of the cost shock. It is assumed that a TAC is set and individual fishing rights are distributed or auctioned as ITQs. Optimal sub-allocation of fishing rights occurs via a competitive secondary market. The TAC is assumed to bind and only interior solutions are examined. The regulator's dynamic programming problem is

$$V_t^r(x_t) = \max_{e_t} p(x_t - e_t) + E_t \left[- \int_{e_t}^{x_t} \eta_t c(s) ds + \delta V_{t+1}^r(x_{t+1}) \right] \quad (11)$$

With no correlation, the value of waiting for the cost shock to be realized is derived solely from the change in the marginal cost of fishing and is equivalent to the difference in expected values of the two management regimes. When shocks to cost and growth are correlated, some interesting management implications follow.

Proposition 3. When correlation reinforces the direct effect of a cost shock on optimal escapement, the value of waiting for information about the cost shock is greater than without correlation. When the effect is opposing, the value of information about the cost shock is, in general, lessened.

The theme behind Proposition 3 can be gleaned from Table 2. Consider Example 7, where a negative shock implies decreased future growth, and replacement incentives exist. The sole owner must balance the incentive to take advantage of lower costs and harvest more fish now with the increased marginal value of escapement. The indirect effect of the shock dampens the incentive to harvest more today, and therefore the optimal harvest level will deviate less from the ex-ante than it would if correlation were not considered. The final column of Table 2 depicts these situations clearly. In those entries where the direction of optimal escapement is known with certainty, the value of information is intensified by correlation. In those entries containing question marks, optimal escapement is likely to be in the neighborhood of the regulator's ex-ante prescription and correlation reduces the value of information¹⁵.

This has significant implications for management of fisheries. Although more information is always better from a diagnostic angle, malleability in regulatory implementation levels after the start of the fishing period is often difficult to justify politically, and so harvest allocations are generally set the fishing season commences. This analysis suggests that the value of information about the cost shock is mediated by correlation. In some fisheries, waiting may make little difference in the ultimate target set. In other fisheries, correlation may increase the value of waiting, and so management might be better served by adjustable targets.

Other control options

Alternatively, the regulator could choose to implement harvest targets by imposing a per-unit fee on harvests or an input control such as an individually tradable effort quota system (ITE). These mechanisms are also decentralized in nature, but instead of imposing a firm cap on the amount of fish caught in a period, harvests depend on the realized value of η_t . The advantage of landing fees or ITEs is that when costs are lower than expected – thereby lowering optimal escapement – the decentralized escapement level is also lower (though still second best to the sole owner). In the case of landing fees, this response is based on an underlying optimization problem faced by individual firms. With ITEs, the response is passive and based on the relationship between marginal effort requirements and marginal costs¹⁶. With correlation, the optimal level of escapement given a cost shock now depends on both direct and indirect effects. For instance, consider Example 1 in Table 4. If there is a positive cost shock, the direct effect increases optimal escapement. At the same time, positive correlation implies growth of escapement is expected to be higher. If ROI incentives dominate, the indirect effect is to increase optimal escapement even further. ITQ hold escapement constant, whereas landing fees or ITEs will lead to higher escapement. Referring to Table 2, those cases for which the change in optimal escapement can be signed (the final column) will tend to favor landing fees or ITEs. Those cases that cannot be signed indicate opposing direct and indirect effects, and will tend to favor ITQs.

CONCLUSIONS

This research considers whether a standard assumption by economists – that economic and biological uncertainties in fisheries are independent of one another – should be viewed with skepticism. Six examples of commercially exploited species suggest that environmental disturbances can cause correlated deviations in current period costs and future biomass. Using a simple analytical model, a number of intuitive results are generated. The realization of a

cost shock will have direct *and* indirect effects on optimal escapement. The direct effect is associated with the change in marginal cost felt today, shifting optimal escapement in the direction of the shock. The indirect effect results from correlation between the cost shock and the random element of biological growth. The indirect effect of a cost shock can have opposing impacts on optimal escapement based on the structural placement of the growth shock, the structure of the growth function, and the structure of the cost function, implying that economists using general models would do well to justify a particular approach, or at the very least examine how different structural assumptions affect model outcomes. If the direct and indirect effects of a cost shock impact optimal escapement in the same direction (if the final column of table four can be signed), there is additional value in having the ability to adjust targets after the cost shock is realized. If the two effects counter each other, the value of waiting is lessened. This result implies there is potential benefit associated with a large initial scientific investment aimed at understanding the sources of variability of fisheries and how different stochastic elements might be related. This would give managers the opportunity to design regulations that allow intra-period adjustment to targets (e.g., after the cost shock – or the environmental driver – is realized).

Of particular interest is the case of positive correlation and a management goal of compensating for expected deviations in future growth (replacement incentives), specifically the possibility that harvest costs might decrease at the same time future biological growth declines. As discussed above, the blue crab fishery in Georgia may have been subject to such a phenomenon preceding the stock collapse between 2000 and 2002. The motivation for this paper was observation of the Georgia blue crab fishery and the collapse experienced earlier this decade following onset of severe drought. Low river flow appears to impact harvests positively and biomass negatively, potentially due to the fact that fishermen are aware of the movement patterns of crabs in response to river discharge and place their traps accordingly. There are corollaries to this example that have been observed in other fisheries. Evidence suggests the overfished northern cod fishery underwent temperature induced changes to schooling behavior prior to its ultimate collapse, leading to hyper-stable CPUE (Rose & Kulka, 1999). Other potential examples exist as well. For instance, forage fish are under pressure from the rise of aquaculture and other land-based uses (Naylor et al., 2009). This activity is largely unregulated and the extent of exploitation is difficult to ascertain, but as utilization increases, there will likely be impacts higher up the food chain. Hypoxia in the Gulf of Mexico is associated with changing fish distributions, often pushing species (e.g., shrimp) to the edges of hypoxic zones. Fishermen are known to congregate on these edges to take advantage of higher catch rates¹⁷. These and other ecosystem-scale disturbances may create stress in food webs, leading to lower growth rates and predictable behavior by fish as they search for energy. In the absence of observing stocks directly, dealing with positive correlation presents an identification problem: in fisheries where CPUE is stock dependent, a drop in cost per unit harvested could be due to either a larger-than-expected stock or a negative environmental shock – optimal responses under the two possibilities are clearly different. For these fisheries, predictive models and malleable regulations are particularly valuable.

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Appendix: Derivation of the comparative static given by (8).

To develop the numerator of (8), take the derivative of (7) with respect to η_t

$$c(e_t^*) + \delta \int_a^b g_e(e_t^*, \theta) (p - c(g(e_t^*, \theta))) dF_\eta(\theta; \eta) \quad (A1)$$

The first term of (A1) is the direct effect of η_t on the current cost and the second is the indirect effect on the marginal value of escapement. The latter is evaluated via integration by parts

$$\begin{aligned} \delta \int_a^b g_e(e_t^*, \theta) (p - c(g(e_t^*, \theta))) dF_\eta(\theta; \eta) &= \delta g_e(e_t^*, \theta) (p - c(g(e_t^*, \theta))) F_\eta(\theta; \eta) \Big|_a^b \\ &\quad - \delta \int_a^b (g_{e\theta}(e_t^*, \theta) (p - c(g(e_t^*, \theta))) - g_e g_\theta c') F_\eta(\theta; \eta) d\theta \end{aligned} \quad (A2)$$

The first term on the right hand side of the equality is simply zero. The second term, along with the direct effect, forms the numerator of (8).

¹ Adult females will traverse the salinity gradient during the spawning cycle, releasing eggs in the open ocean. Males tend to inhabit intermediate salinities for their entire life cycle (Hill, Fowler, & Moran, 1989).

² Personal communication with representatives from the Georgia DNR (GDNR) and commercial crabbers.

³ Ecological Monitoring Trawl Survey, GA DNR, Coastal Resources Division, Marine Fisheries Section, Research and Surveys Program.

⁴ El Niño (La Niña) “events” are associated with warmer (cooler) than normal sea surface temperatures and an extension (contraction) of the warm pool in the western tropical Pacific Ocean. Lehodey uses the southern oscillation index (SOI) as a proxy for indicating the subsequent appearance of an El Niño or La Niña event.

⁵ For a more detailed exposition of the effects, see Lehodey (2000)

⁶ The latter of these could result from environmentally-driven variability in catchability.

⁷ Realistically the cost shock would be a continuous variable. This simplification is made for reasons of tractability and does not qualitatively alter the results.

⁸ As the optimal escapement level turns out to be state-independent, path-dependency in the control is not an issue. Therefore, if a mechanism is preferred to others in one period, it is preferred to others in all periods.

⁹ Note that the sole owner’s choice of mechanism is irrelevant; once the cost shock is known, the efficient harvest can be achieved by any of the three mechanisms.

¹⁰ Net revenues are concave in escapement (linear revenues and convex costs). Strict concavity in the growth function implies the second term of (3) is a concave function as well.

¹¹ $F_\eta(\theta; \eta)$ is the partial derivative of the CDF of θ with respect to η . The distribution $F(\theta; \eta_1)$ has first-order stochastic dominance over $F(\theta; \eta_2)$ if $F(\theta; \eta_1) \leq F(\theta; \eta_2)$. In the context presented here, this implies the distribution $F(\theta; \eta_1)$ results in a higher expected value for the growth shock than the distribution $F(\theta; \eta_2)$. This can be thought of as a right-ward shift in the probability distribution function.

¹² $p - c(\cdot) > 0$ (\cdot) is evaluated at the next-period’s stock level, and $c' < 0$.

¹³ Costello, Polasky, & Solow, 2001 do not fully investigate the form of the comparative static, and make this conclusion with a generalized growth function and shock.

¹⁴ High fluctuations in biomass can lead to changes in the trophic structure of an ecosystem (Jackson et al., 2001). Economic reasons could include the desire to maintain stable harvests each period for employment or due to the presence of significant fixed costs.

¹⁵ It is possible that small shocks to marginal costs portend large shocks to growth, in which case the opposing indirect effect could be more than twice as large as the direct effect and therefore optimal escapement would deviate in the opposite direction at a higher rate than under no correlation. That possibility is ignored.

¹⁶ For a formal exposition, see (Kennedy, 2010).

¹⁷ Personal communication with NMFS biologists, SEFSC.