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Gaming the System: Bio-Economics, Game Theory, & Fisheries Management

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I. INTRODUCTION & SYNOPSIS

The current commercial fisheries landscape is dismal. Most major American fishing regions are in crisis, with nearly 80% of the nation's known commercial species are now overfished or harvested to their sustainable limit. The Atlantic cod stocks have been decimated, causing that cod industry to collapse completely in 1994. Another centuries-old mainstay of fishing in the North Atlantic, Georges Bank, was closed to commercial fishing, with scientists saying it may never recover. Internationally, the current status of fisheries is similarly worrisome. The U.N. Food & Agriculture Organization (FAO) has recently issued reports concluding that “about 70 percent of the world's commercially important marine fish populations [are] fully fished, overexploited, depleted, or slowly recovering.” Many scientists agree that we are facing a crisis in world fisheries, some estimating a 90% removal of predatory fish globally.

How can we account for these failures? Traditional neo-economic theory holds that actors are rational: they will seek to maximize profit, necessitating consideration of long-term viability, and therefore a sustainable harvest will result. As excessive entry, overcapacity, and resulting overharvest reduce profits—theory predicts—effort will naturally curtail and exit will occur until equilibrium is reached. If this is correct, how can we account for such poor results?

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3 Kirsten M. Batkin, *supra* n.1 at 616–17.
One contributing factor may be overreliance on understanding the science of ecosystems and population dynamics, and too little attention paid to the science of actors’ decision-making, incentives, and concomitant harvesting behaviors. While we commit a great deal of scientific, budgetary, and regulatory attention to the former, perhaps the latter have received short shrift. As we have experienced, anthropogenic contributions have as much potential to substantially affect population levels as the physical science underlying natural systems.

At the very least, then, it seems indisputable that past analytical approaches have failed in some important (and tragic) ways. A re-examination and enrichment of the tool set—with particular attention to harvesting behaviors—is needed to effect genuinely sustainable fisheries management. This paper explores the promise of game theory, how it fits well with the analytics of open access fisheries regimes, and what policy implications it suggests for sustainable management.

Game theory is the study of the ways in which complex strategic interactions among economic agents produce outcomes, both desired and unintended. The protection of many “migratory” natural resources—such as “straddling” fish stocks—requires cooperation and coordination between multiple entities, such as individuals, businesses, agencies, and local and national sovereigns. While the details of each resource management problem are different, they all have one particular feature in common: they necessarily involve interdependencies among parties’ desired outcomes and strategic, self-interested decision-making informed by the expected actions of the other agents. As such, game theory can help natural resource managers analyze and understand how agents make decisions and how their behaviors affect both individual and aggregate gains and losses.
Fisheries management coordination represents an emblematic “coalitional” challenge: though renewable, migratory fish stocks are a depletable “commons” resource, subject to a large number of actors, all seeking their rational individual interests with the assumption that others will act similarly. Thus, the policy problem presented by fisheries is fundamentally a one of developing an effective set of incentives for each entity to make self-interested, net-benefit decisions that also result in sustainable outcomes.

This paper argues that game theory provides powerful, effective new tools to analyze externalities that occur in the context of strategic, multi-party, interactive decision-making. I will attempt to treat this as a non-technical paper and avoid the complex mathematics better left to economists and mathematicians. Instead, a more achievable goal is to illustrate how high-seas open-access fishing is virtually identical to a game situation, treat the fundamentals game theory, and demonstrate that game theoretic analyses is well-suited and fruitful for designing effective policy responses to fisheries management, particularly with respect to the straddling stocks problem. Indeed, one seminal fisheries scholar has been so bold as to claim that “[e]conomists cannot analyze the economics of the management of such fisheries, with the hope of providing useful insights to policy makers, other than through the lens of game theory.”

Section II reviews some key features of the fisheries resource to ground the discussion. Section III provide a brief overview of game theory. Section IV argues that management of trans-jurisdictional straddling stocks is very much like a standard game theoretic situation and applies a game theoretic analysis to fisheries. Section V briefly touches on some possible challenges the current high seas fisheries legal regime presents for reaching optimal collaboration between parties. In Section VI, this paper discusses the policy implications of a

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7 *Id.*
game theoretic treatment of international fisheries management: what insights do we glean from game theory, and what policies does game theory recommend?

II. THE BIOECONOMICS OF FISHERIES

To apply a game theoretic approach to an open-access fisheries situation, we first have to understand the basic dynamics of the resource and underlie the incentive structure and other game elements. Bioeconomics is a well-suited discipline that essentially applies economic concepts and models to dynamic natural systems, and has been especially robust in its treatment of fisheries.

Two predominant tenets synopsize the methodology. First, open access harvest in dynamic natural systems can lead to resource collapse if stocks are harvested past a certain critical threshold that makes a crash to zero, rather than regeneration, inevitable. Second, dynamic natural systems respond to regular supply and demand forcings in ways characteristic of other economic systems.

Of central importance here is the notion that the relationship between harvesters and fish stocks exhibits “cyclicality”: high harvest attracts more harvesters, but this influx lowers the stock, causing reduced profits and harvester exit, which in turn allows the stock to recover, and so on. Traditional economic theory predicts that losses induce market exit, which in turn allows natural growth to exceed harvest so that the stock increases, and eventually a return to profitability, where the cycle then repeats.

In short, this traditional cyclicality model predicts equilibrium of both capacity and effort.

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9 See, e.g., Lee G. Anderson & Juan Carlos Seijo, BIOECONOMICS OF FISHERIES MANAGEMENT (2010).
11 Colin W. Clark, MATHEMATICAL BIOECONOMICS 9–12 (2d ed. 1990) (describing basic functions used to evaluate stock changes).
12 Jason Scott Johnston, supra n.10 at 857.
While it seems undeniable that the interplay between biological population dynamics and economic entry/exit decisions is likely to generate cycles or other periodicity in an open access resource, fisheries experience calls the capacity and effort equilibrium proposition into serious question. There is much to suggest that overcapacity in capture fisheries is one of the most important factors threatening the long-term viability of exploited fish stocks.\(^\text{13}\)

The fundamental tenet of bioeconomics is that whether open access harvest drives the stock to zero depends upon how the economic dynamics (i.e. entry/exit) intertwine with biological dynamics (i.e. the natural growth of the harvest target).\(^\text{14}\) Entry and exit decisions differ when harvesters base them on rational expectations about the present value of future harvest. For those rational actors, exit from the market will likely occur even when there is still residual, albeit short-term, profitability, with the more myopic\(^\text{15}\) harvesters still not being triggered to exit.\(^\text{16}\) Typically, the faster harvesters exit as stock diminishes, the lower the chances that the stock will drop past the critical threshold or to zero.\(^\text{17}\) If this critical threshold is surpassed, though, the stock will eventually decline to zero.\(^\text{18}\)

Unfortunately, such a simplistic model does not match what has been empirically

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\(^{13}\) See, e.g., P. M. Mace, Developing and Sustaining World Fisheries Resources 98–102, in SECOND WORLD FISHERIES CONGRESS (D.A. Hancock et al. eds., 1997).
\(^{14}\) It is an ecological truism that “everything affects everything else,” and this should be the touchstone of fisheries management. I credit Jeffery G. Miller, United States Pollution Control Laws, 13 PACE ENVTL. L. REV. 513, 516 (1996), for this simple but powerful reminder.
\(^{15}\) For discussions of “myopic loss aversion” and other well-documented psychological phenomena and their effects on the decision-making of economic actors, see, e.g., Joshua D. Wright and Douglas H. Ginsberg, Behavioral Law and Economics: Its Origins, Fatal Flaws, and Implications for Liberty, 106 NW. U. L. REV. 1033 (Summer 2012) and Eyal Zamir, Loss Aversion and the Law, 65 VAND. L. REV. 829 (April 2012).
\(^{17}\) This concept of “critical depensation” is now a well-established phenomenon: where the population drops to a particular critical point due to open access harvest, slow exit, or even non-human forcings, then the natural growth rate function will become negative and almost guarantee decline to zero. See Dean Lueck, The Extermination and Conservation of the American Bison, 31 J. LEGAL STUD. 609, 616–17 (June 2002).
\(^{18}\) For readers more mathematically-minded than myself, this is expressed that where there is a population level \(x_e\) such that \(f(x) < 0\) for all \(x < x_e\), once \(x\) falls below \(x_e\) the population will inexorably fall to zero. See, e.g., Peter Berck, Open Access and Extinction, 47 ECONOMETRICA 877 (1979).
demonstrated in practice. Natural resources management has customarily been fragmentary and reductionist, seeking to isolate, analyze, and control individual aspects of the natural system.19 Such approaches are bound to fail, however, because ecosystems are diverse, overlapping, and interrelated,20 operating as complex dynamic systems characterized by many mutually interdependent components.21 And when one considers multiple anthropogenic inputs, themselves complex and interdependent, it seems a wholly unremarkable proposition that ecosystems do not inexorably tend toward equilibrium22 and can exhibit nonlinearity23 and inherent stochasticity.24

Open seas fishing is an archetypal “rule of capture” context: the first party to reduce the fish to controlled possession obtains ownership.25 Awarding property rights to the first person to develop a resource seems to have the advantage of incentivizing development effort and, ostensibly, awarding the property right in the resource to the person with the lowest cost and/or highest productivity. Unfortunately, though, the rule of capture establishes a “race” situation which generates clear inefficiencies by encouraging excessive entry and harvest. It also allows harvesters to ignore the effect of their own extraction in lowering others’ use value, which is

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20 Bradley C. Karkkainen, supra n.19 at 190.
22 See Daniel B. Botkin, Discordant Harmonies: A New Ecology for the Twenty-First Century 10, 62 (1990); Holling et al., supra n.21 at 354 (“The linear, equilibrium-centered view of nature no longer fits the evidence, and is being replaced by a non-linear, multi-equilibrium view.”).
23 See Holling et al., supra n.21 at 352–53 (“A general characteristic of resource management problems is that they are fundamentally non-linear in causation ... demonstr[ing] multi-stable states and discontinuous behavior in both time and space.”).
often termed an “externalities” problem. In the absence of effective institutional arrangements to constrain this race, excess capacity and overexploitation is typically the direct outcome of these competitive and costly development races to exploit common property resources.

Thus, managing natural resources on an open access basis—under the rule of capture—results in overharvest. Hardin’s Tragedy of the Commons, the customary open access problem, illustrates this nicely. Any individual harvester’s increased productivity depends on her own efforts, but at the same time other harvesters’ similar increased efforts in turn diminish that productivity. Phrased alternatively, we could say that harvest efforts create an externality in the form of decreased present productivity: past harvest causes a fall in the stock that makes future harvest efforts less productive, and causes increased present harvest just to maintain productivity.

For the purposes of this paper, we need not attempt a definitive answer to the question of whether the rule of capture and open access will always, or ever, lead to the overexploitation and eventual extinction of the fish stock or other resource. We need only note the less disputed characteristics of the open access system to which game theory is to provide a (hopefully) useful application. The key insight here is that when each user is small relative to the total number of users, they all ignore the marginal effect of their take on other users and increase harvest levels

26 “Rent dissipation” is also a common phrase for this failure to individually internalize the collective cost of capture effort, but “externality” is effective and avoids unnecessary obfuscation.
28 Jason Scott Johnston, supra n.10 at 860.
29 Id.
30 The “standard” bioeconomic model, (what is known as a “compensatory” growth function) and cost is linear, extinction cannot result. Peter Berck, Open Access and Extinction, 47 ECONOMETRICA 877 (1979) (where f(x) is assumed to be such that f(x) >= 0 and f” (x) < 0 for all x. Johnston, for example, argues contra Gordon and other neo-classical advocates that the equilibrium harvest level is bounded by the zero profit, rent dissipation condition, such that it is theoretically and empirically fallacious to claim that open access harvest leads to resource extinction. Cf. H. Scott Gordon, The Economic Theory of a Common Property Resource: The Fishery, 62 J. POL. ECON. 124 (1954) (arguing that fisheries are over exploited because of their common property nature).
until average product equals average cost.\textsuperscript{31}

III. GAME THEORY: OVERVIEW & SUMMARY

Overly-complicated descriptions of game theory abound, but at bottom it is merely the formal study of strategic decision-making among interested agents as they seek to Maximize desired outcomes. To illustrate, assume there are a number \((n)\) of agents \((a)\), such that \(a = \{1\ldots n\}\), each seeking the same outcome. Each can choose different strategies \((s_a)\) from a set of strategies \(\{S_a\}\) to realize this outcome. Player 1 can choose \(s_1, s_2, \ldots\) from her set \(S_1\); Player 2 can choose \(s_1, s_2, \ldots\) from her set \(S_2\); and so forth for each agent. Depending on these respective strategic choices, each player \(a\) will realize payoffs that are a function of the aggregate of all decisions, which we can designate \(p_a (where \(p_a = f\{s_1, s_2, \ldots s_a, \ldots s_n\}\))\textsuperscript{32}. Simply put, each player will have strategies available to them, and each player’s payoff depends on both their own choice of strategy and the choices of all the other players. The extent to which a player is able to consider others’ decisions depends, naturally, on the information available to each player at the time of decision and on the order of play.

A game theoretic approach such as this employs at least three key assumptions. First, it treats actors as “interested,” i.e. they seek to Maximize their individual rational goals.\textsuperscript{33} As a corollary, this implies that actors will respond to incentive structures designed to affect actors’ behaviors. Second, whenever actors seek to achieve a desired goal or set of goals, they tend to behave strategically. That is to say, as actors seek to achieve their individually-valued objectives their decisions will be fundamentally informed by expectations that other agents will behave

\textsuperscript{31}Jason Scott Johnston, supra n.10 at 860.

\textsuperscript{32}These symbolic representations are fairly standard in game theory—the notations here are my slightly modified version of Gibbons’. See Robert Gibbons, A PRIMER IN GAME THEORY 8–9, 13–15 (1992).

\textsuperscript{33}For the purposes of this paper, I will be assuming economic goals unless otherwise explicitly stated. But it is worth noting that various actors—particularly governmental ones—may often value non-economic goals, such as domestic political payoffs or ideological consistency.
analogously to themselves. Game theory’s third key assumption is that there is an optimal outcome (“equilibrium”), wherein all players have maximally achieved their preferences.

Like all assumptions, these are of course open to questioning and challenge. But since we are adopting game theory here as a proposed heuristic, not an exclusive normative proposition, we need not establish the absolute veracity of these assumptions. We can just acknowledge their contingent status, and proceed to demonstrate the utility of game theoretic tools in a fisheries management context. As we shall see, the policy challenge for fisheries entails designing an appropriate set of incentives for each of the decision-making entities to prefer cooperation over unilateral action.

A. Modeling the game

The first stage in a game theoretic approach is to systematically model the game, which should include at least four central components. One must identify the actors—these are the “players” in the game who make decisions. The model must also determine the rules of the game, including the “moves” (actions available to each player at each point in the game) and the order of play (whether player actions are simultaneous or sequential). Another key modeling component is to identify the information available to players at the time they make decisions. Lastly, the model should account for the “outcomes,” i.e. the payoffs for the players that result from and incentivize different combinations of actions.

B. “Solving” the game via Nash equilibrium determination

The second stage in a game theoretic approach is to “solve” the game, which can be done in a variety of ways. We saw in the modeling stage that the game consists of players who make moves, by a set of rules, in an attempt to achieve optimal outcomes. “Solving” the game is really

34 Though I have modified this standard schema somewhat, the choice of four modeling components and a large majority of their content are borrowed from Eric Rasmusen, GAMES AND INFORMATION: AN INTRODUCTION TO GAME THEORY 22–25 (1989).
just determining, quantitatively, the best strategy choices for each player given the overall context of the game (i.e. all players’ strategy options and concomitant payoffs). This game solution is commonly called its “equilibrium.”

While there is an element of choice for the modeler regarding the “equilibrium,” the most common for bimatrix games is called the Nash equilibrium. A strategy is “Nash” if no player has incentive to deviate from his strategy, given that the other players similarly do not deviate.35 The way to approach Nash equilibrium is to propose a strategy combination and test whether each player’s strategy is a best response to the others’ strategies.

C. Bimatrix games

Bimatrix games provide an excellent, accessible example to illustrate standard game modeling, solving, and equilibrium determination. In bimatrix games, there are two players who effectively make their moves simultaneously without knowing the other player's action. For brevity, I will illustrate using the classic, oft-cited Prisoner’s Dilemma (PD). The essence of PD is that two prisoners, when faced with the option of “ratting out” the other out in exchange for reduced or no punishment, will always choose to do so, even when cooperating (i.e. each staying silent) would mean that each achieves their highest possible payoff. In this non-zero sum game, each individual prisoner will consider all of their options, assume the other will realize the same, and re-assess their options to take into account the other’s rational decision-making. Because of the perceived likelihood that the other will talk first, it becomes a “race” for one actor to capture the gain for before the other does so at her expense, and the result is a lower payoff than would have been achieved if the actors had cooperated. As we will see later, this “race” psychology has important implications for a game theoretic analysis of fisheries dynamics in particular.

Represented graphically, we can see that from either prisoner’s perspective, their optimal
decision is to confess rather than collaborate and cooperate with the other prisoner. The first
number in each ordered pair represents Player 1’s (P1) payoff ($p_{1\cdot}$) for each move given P2’s
move, and the second number represents P2’s payoff for each P1 move.\footnote{For simplicity, these are supposed numbers. In a real game model, one must have some reasonable basis on which
to estimate the relative player payoffs—the weaker this basis, the weaker the predictive model. Here, for illustration
purposes, let us assume that there is some reasonable basis for these quantitative payoff representations.}

<table>
<thead>
<tr>
<th>PLAYER 1</th>
<th>Squeal ($s$)</th>
<th>Collaborate ($c$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Squeal ($s$)</td>
<td>2, 2</td>
<td>4, 0</td>
</tr>
<tr>
<td>Collaborate ($c$)</td>
<td>0, 4</td>
<td>3, 3</td>
</tr>
</tbody>
</table>

The incentive structure mandates that P1 always choose to squeal: if P2 decides to
squeal, P1 should too because her payoff is 2 instead of 0. And if P2 decides to collaborate, P1
should still squeal, because her payoff is 4 instead of 3. The crucial takeaway is that for all P2
moves, P1 optimizes the payoff by non-cooperation: no matter what P2 decides to do, P1’s
payoff is maximized by choosing to squeal.\footnote{In game theory parlance, where this occurs and one choice always produces the optimal outcome given others’
decisions, the strategy choice is said to “dominate.”} Likewise for P2: if P1 squeals, P2’s best choice is
to squeal as well ($p_{2(s)} = 2$ vs. $p_{2(c)} = 0$), and to squeal if P1 chooses collaboration ($p_{2(s)} = 4$ vs.
$p_{2(c)} = 3$). To produce a different result, a change in the incentive structure is required that is
sufficient to make the collaborative action payoff clearly better than the unilateral, selfish action.
The inevitability of this outcome is accentuated where the game is played only once or a few
times, thus not allowing trust or social punishment deterrence to develop.

IV. LET THE GAMES BEGIN: A GAME THEORETIC APPLICATION TO FISHERIES MANAGEMENT
As we have seen, many key features of fisheries resources and their management closely resemble game situations. There are multiple players involved, each competitively seeking an individual harvest that lends itself to quantification as a payoff, and each will take into account others’ respective moves payoffs in the course of their own strategic decision-making. Moreover, players will need to be shown the clear superiority of cooperation and collaboration before being effectively incentivized to eschew unilateral action.

We will continue focusing on one of the biggest challenges to global sustainable fisheries, that of migrating species of fish (aka “straddling” fish stocks). Straddling stocks (i.e. those that migrate between the EEZs\textsuperscript{38} of several countries and the high seas) represent as much as one third of fisheries catches\textsuperscript{39} and can be likened to cross-boundary animal migrations: effective preservation or conservation typically requires coordinated actions on the part of a variety of public and private entities.\textsuperscript{40} The interested actors—i.e. the “players”—may include high seas fishing fleets, coastal states, government agencies within a nation, or the governments of different sovereign nations (e.g. Distant Water Fishing Nations). It is the nature of fish stocks and economies themselves that no single entity can or does have full control over the set of human actions that determine the long-term sustainability of a fish population. This therefore creates another type of inherent interdependence amongst decision-makers—in other words, the success of conservation actions taken by one entity depend very much on what other entities

\textsuperscript{38} See 16 U.S.C. § 1811 et seq. The Magnuson Fishery Conservation and Management Act (Magnuson) established what were originally designated Fishery Conservation Zones (“FCZs”), which eventually became the 200 mile Exclusive Economic Zone (“EEZ”) off the coast of the United States after Presidential Proclamation 5030, 3 C.F.R. 22 (March 10, 1983). See also Eldon V.C. Greenberg, Ocean Fisheries 371, 387, in SUSTAINABLE ENVIRONMENTAL LAW (C. Campbell-Soehn et al. eds., 1st ed. 1993).


\textsuperscript{40} David N. Cherney, Securing the Free Movement of Wildlife: Lessons from the American West’s Longest Land Mammal Migration, 41 ENVTL. L. 599, 612–15 (Spring 2011).
decide to do.\textsuperscript{41}

The notion of managing throughout a species’ “full life cycle” is a core concept of U.S. fisheries management as part of the essential fish habitat definition,\textsuperscript{42} national standards,\textsuperscript{43} and other Magnuson regulatory provisions. Because the migratory and impermanent nature of straddling stocks, they will migrate into and out of the U.S. EEZ as part of their life cycle, thus requiring international co-operation to manage these species. This should be instantly recognizable as a classic, multi-player situation to which a standard game theoretic heuristic can be applied. While simpler forms of game theoretic fisheries modeling have been occurring for three decades or more, straddling stock modeling has languished and remains underdeveloped.\textsuperscript{44}

For all of these reasons, then, effective management of a straddling stock requires a mechanism for coordinating and disciplining the efforts of multiple players. Although in principle players could simply agree among themselves to coordinate their efforts, we can expect all the familiar kinds of coordination problems—free-riders, holdouts, and the sheer informational costs associated with informing, organizing, and maintaining communication among a large number of parties. Consequently, purely voluntary, non-institutionalized coordination among players in this context is likely to arise only rarely and be sustained over extended time periods even less frequently.\textsuperscript{45}

A. A harvest game

Recall our PD example (Sec. III-C, p.10). Simplicities notwithstanding, this model can be readily applied to fisheries. Following standard methodology, let us first identify the players: two countries, A and B, who are the two most significant harvesters of a particular fish stock

\textsuperscript{41} Kathleen A. Miller, supra n.27 at 576.
\textsuperscript{42} 50 C.F.R. § 600.10.
\textsuperscript{43} 50 C.F.R. § 600.305.
\textsuperscript{44} U.R. Sumaila, A review of game-theoretic models of fishing, 23 MARINE POLICY 1–10 (1999).
\textsuperscript{45} Bradley C. Karkkainen, supra n.19 at 213–14.
(accounting for 98% of the depletion). Each country has two moves available: reduce their harvest, or not reduce. The order of play is simultaneous: each country is fishing contemporaneously, and each has to make its decision at the same time. While neither country has “perfect information,” each will understand enough about industry standards to accurately approximate others’ harvest levels, locations, techniques, and incentives to estimate the payoffs of each strategy. Let us suppose the following payoffs represent the net of each country’s comprehensive cost-benefit analysis.

<table>
<thead>
<tr>
<th></th>
<th>COUNTRY B</th>
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<tbody>
<tr>
<td></td>
<td>Reduce ((R))</td>
</tr>
<tr>
<td>COUNTRY A</td>
<td>Reduce ((R))</td>
</tr>
<tr>
<td>Not Reduce</td>
<td></td>
</tr>
</tbody>
</table>

Again, no matter what move Country B makes, Country A’s optimal decision is to not reduce: if B reduces, A’s payoff is +1 higher for not reducing (6 instead of 5); and if B does not reduce, A’s result is again +1 higher for not reducing (-3 instead of -4).\(^{46}\) It is likewise from B’s perspective: B’s rational choice is to not reduce no matter what A does, because they will obtain a positive expectation of +1. All the scientific understanding of ecosystem and population dynamics in the world will be insufficient to avoid this universally-undesired outcome—the only way is to change the structure of payoffs such that cooperation is the best strategy for each player, and that analysis is emphatically within the province of game theory.

Ideally, each player would seek a payoff comprised of both the net present value of the

\[^{46}\text{Implementing the standard nomenclature, we can express this relationship as } p_{A(NR)} = f\{s_{B(R)}\} > p_{A(R)} = f\{s_{B(B)}\}.\text{ Though one of its virtues is brevity, symbolic expression is also more abstract and less clear to most of us, so I will instead favor clarity and simplicity wherever possible.}\]
harvested fish after costs and any lost future reproductive potential of the fish population.\textsuperscript{47}

However, when two or more players are harvesting from the same population, the ability of each to take those future values into account is constrained by the zero-sum nature of the resource: an animal that one player leaves unharvested may very well be taken by another. Each player's harvest subtracts economic units and renders them unavailable to other players. Thus, in the absence of a mechanism to control incentives to engage in a harvesting race, the outcome is likely to be a predictable “tragedy of the commons” that will tend to dissipate the potential economic value of the shared resource and may greatly reduce the size of the animal population and its resilience to other stresses.\textsuperscript{48}

Though out of necessity we have focused on simpler, two-player games, more complex, multi-actor situations are equally amenable to game theoretic analyses. A good example of an actual application is Pacific Southern Bluefin Tuna. New Zealand, Australia, and Japan were the three players, and they sought the same migratory stock in the Pacific. To help these countries decide what the harvesting quotas should be, analysts modeled the game with three players, each with up to four variables (representing the four age groups of the fish stock), harvesting a dynamic system (the open seas fish population).\textsuperscript{49} The next step was to determine the equilibrium, represented by the maximization of the sum of the payoff functions (see Sec III, p.9). Both the non-cooperative and cooperative payoffs were modeled and calculated, and then compared.\textsuperscript{50}

\textsuperscript{47} Colin W. Clark, \textit{Mathematical Bioeconomics: The Optimal Management of Renewable Resources} 4–5, 26 (1976); Kathleen A. Miller, \textit{supra} n.27 at 583.

\textsuperscript{48} Gordon R. Munro, \textit{The Optimal Management of Transboundary Fisheries: Game Theoretic Considerations}, 4 NAT. RES. MODELING 403 (1990).


\textsuperscript{50} Because single-period models are limited to demonstrating the effects of past activities on current stock, modeling of the steady state harvest and long-run resources levels is often more instructive. \textit{See} Robin Brooks, Michael Murray, Stephen Salant & Jill C. Weise, \textit{When is the Standard Analysis of Common Property Extraction under Free
Without going into the very sophisticated mathematics that was used to calculate the various solutions and their payoffs, the modeling suggested that higher quotas than the original one could allocated to the three parties.51 Also unexpected and interesting was the result that Australia should be eliminated from fishing if Australia and Japan were to enjoy a maximization of their rewards.52

B. Two-level games

To add a further wrinkle, not only can we add additional players, we can increase the variable complexity of each player’s strategic considerations. Probably the most important, any game theoretic approach to fisheries management will have to incorporate the two-level nature of the game. That is to say, in addition to other states as rational players, each state player must account for its own domestic interest group players that often have different and conflicting preferences—these groups will necessarily influence a state’s emergent international game strategies.53 Some scholars have noted that international state games are really two-level games, in which the game played on the domestic level powerfully influences the outcomes of the international level game.54 These domestic influences include interagency rivalries, incompatible missions, interparty mistrust (between government, business, private landowners, and environmentalists), and all the usual coordination problems that plague any multiparty effort.55 Moreover, ecosystem boundaries are poorly matched to domestic legal, political,

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51 Jacek B. Krawczzyk & Boleslaw Tolwinski, supra n.49 at 8.
52 Id. at 9.
institutional, and jurisdictional scales.\textsuperscript{56}

Though important to flag, this multi-level dynamic cannot be treated here, both due to scope restraints and because, at bottom, the two-level game analysis probably does not change the basic utility of game theoretical treatments and counsels for inclusion of those variables in a states’ international-level strategic payoff analysis. Any full game theoretic approach, though, should take into account collective-action dynamics and problems inherent crafting various potential equilibrium outcomes and the policies designed to effectuate them.\textsuperscript{57}

V. THE NEXT MOVE: CRITIQUES

The potential cost, required sophistication, and other practical resource limitations are only one set of foreseeable difficulties in employing game theoretic analyses. In addition to this very real and important critique, there are some important dissimilarities and limits to the utility of PD as an analog to our application. First, whereas PD involves non-iterative, single-period interactions with strangers one never expects to encounter again (i.e. played one time only), the international open-access fishing milieu by contrast is highly iterative. Rather, governmental policy-setting and resource managing entities would expect repeated encounters and, ideally, to develop and maintain long-term relationships. Thus, policy makers can and should consider mechanisms to reward cooperation and punish non-cooperation and defection. Secondly, PD is relatively simplistic: many real-world contexts, like fisheries, involve a far greater number of players, range of strategy options, incentives, and relative payoffs.

Game theory has a robust answer for these situations via models—such as Bayesian games,\textsuperscript{58} multi-stage games,\textsuperscript{59} and coalitional games\textsuperscript{60}—that do incorporate this advanced degree

\textsuperscript{56} Bradley C. Karkkainen, supra n.19 at 212.
\textsuperscript{58} See, e.g., Robert Gibbons, supra n.32 at 143–149.
of combinatorial complexity found in situations characterized by multiple-actors, trans-boundary stocks, and asymmetric information. The mathematics underlying these games is different, but they are analytically quite vigorous and demonstrate optimal outcomes for all players given other player choices, just as with normal form representations like PD. Though we have had to neglect treatment of these important “extensive form” games in favor of simplicity and brevity, these types of sequential and stage games are much closer analogs to real multi-actor fisheries contexts, and have been fruitfully applied.

But even we can neither fully examine nor immediately implement these more sophisticated game analyses, there is still a great deal of payoff even from examination and utilization of simpler “normal form” games. Even bi- or trimatrix models have been successfully used to illustrate simple but powerful truisms about the way that self-interested rational actors make strategic decisions. As we have examined, one of these foundational truisms is individual rationality: if cooperation is to succeed, it must yield a net benefit for each player vis-à-vis acting unilaterally (i.e. cooperation must leave each player at least as well off as that player would have been in the original situation).61 No player will agree to accept less from a cooperative arrangement than it could achieve unilaterally, these type of “Pareto superior” outcomes are preferred.62

In particular, the psychology of this “race” situation is characterized by the players’ perception that their best or only chance at realizing their optimal outcome is by a) acting at the

62 A “Pareto superior” outcome simply means that no player is worse off and at least one player is better off. For a nice non-technical synopsis of the Pareto concept, see Guido Calabresi, *The Pointlessness of Pareto: Carrying Coase Further*, 100 YALE L.J. 1211, 1216–17 (Mar. 1991).
others’ expense, and b) acting first. It also demonstrates the way in which players assume that others are engaged in a similar self-interested calculus and then adjust their decision-making and behaviors in light of others’ anticipated actions. The fundamental policy implications are too powerful to ignore.

It is true that unilateral conservation actions may return benefits, even considerable ones in some circumstances. Such unilateral conservation actions also could confer benefits to one's neighbors who themselves do not act (the classic “free-rider” problem). But until the payoffs of collaboration are clearly superior to that of purely self-interested unilateral action, cooperative gains are unlikely to be realized. Game theory is instructive about what it takes to make such inter-player collaboration effective, and what incentives are likely to be sufficient in overcoming free-rider and distrust problems such that jointly optimal decisions for the players can be aligned with ecological sustainability.

So, even if the necessary focus on simpler PD and other normal form game analyses is an inferior analog to the real-world complexity of high seas fishing of straddling stocks, they still tell us as much as (perhaps even more than) the physical science of marine ecosystems about what conditions must obtain for maximum sustainable yield. At bottom, even simpler game theoretic expressions reward us by illustrating key assumptions underlying game theory, how they align with the characteristics of fisheries, and how normal form representation games are but one of many constructive game theoretic ways to conceptualize actors’ strategic decision-making regarding open-access natural resources.

VI. MODELING A SOLUTION: POLICY RECOMMENDATIONS

Though it is not necessarily obvious from the preceding—game outcomes vary because they are dependent on the unique inputs of the initial condition—the expert consensus is that...
non-cooperation in management of straddling stocks produces inferior results. Most of the recent scholarship on game theory and its application to migratory fish stock management essentially reaches the same conclusions that—with few exceptions—a PD type of outcome should be expected from non-cooperative management, where all players deem the resource to have been overexploited.

We must always keep in mind that modeling and solving a game is only one step. The ultimate goal is to decide on a desirable set of coordinated conservation actions, secure a stable and workable agreement, and ensure that parties will actually carry out their obligations. Any set of policy solutions is context-determined and unlikely to be a “one size fits all.”

A. Force user cost internalization

As always, the fundamental problem of open-access negotiations is how to incentivize cooperation over unilateral action—only payoffs superior to unilateral action will be deemed acceptable outcomes to rational players. One clear policy implication from our game theoretic analyses is for the policy maker to consider mechanisms to reward cooperation or punish non-cooperation and defection. Often, this involves designing a monitoring-and-punishment enforcement mechanism that will define an equilibrium which will dominate the unilateral action Nash equilibrium. Put simply, this just means changing the incentive structure with penalties such that cooperation has equal or better payoffs for all players.

One mechanism is with potential efficacy is “transferable utility” (i.e. side payments). Given that players often have different preferences and perspectives, joint management of a

63 G.R. Munro, The Optimal management of transboundary renewable resources, 3 CAN. J. OF ECON. 271–296 (1979). This assertion was directly tested and quickly confirmed in D. Levhari & L.J. Mirman, The Great Fish War: An example using a dynamic Courant-Nash solution, BELL J. OF ECON., 11, 649–661 (1980); and C.W. Clark, Restricted access to a common property resource, in DYNAMIC OPTIMIZATION AND MATHEMATICAL ECON. (P. Liu ed., 1980).
64 See G.R. Munro, supra n.6 at 9.
65 Jacek B. Krawczzyk & Boleslaw Tolwinski, supra n.49.
resource is greatly simplified with the possibility of side payments. Among other things, the introduction of side payments shifts focus away from the sharing of harvest amongst the players to the sharing of economic returns from the fishery. In this way, the mechanism for which policy makers are seeking buy-in aligns with the player goals of payoff.

B. Enact Credible Mutual Threat Schemes

Free-riding has historically been a very serious problem in the management of straddling stocks, and is an obvious threat to stability in cooperative resource management agreements. The free-riding problem discourages continued coalition-building, because unilateral action is providing something that each coalition member wants (open-access) but who have bargained away. Thus, any player would be acting irrationally by adhering to an agreement that produces a worse outcome.

The free-rider problem can be addressed with credible mutual threat schemes. If free-riding is made to “cost” more, via “credible threats,” non-cooperation is disincentivized. At the very least, even just clearly categorizing free-riding by non-RFMO harvesters as illegal fishing (not just “unregulated”) eliminates the ambiguity that helps invite free-riding to begin with. Not only does this produce “soft power” in the form of public “shaming” for non-cooperative behaviors, this labeling also makes a whole host of rigorous legal tools available to address the issue.

C. Law as a barrier

The current high seas legal regime failed to conserve straddling and other stocks, it can even act as a barrier to the type of cooperative, coalitional action that game theory recommends to sustain straddling stocks. Unfortunately only the briefest glance is achievable here.

67 See V.T. Kaitala, GAME THEORY MODELS OF DYNAMIC BARGAINING AND CONTRACTING IN FISHERIES MANAGEMENT (1985).
Maximum sustainable yield (MSY) and optimum yield (OY)\(^{68}\) are standards set for the U.S. fishing industry. As we know, however, many fish stocks migrate into and out of U.S. jurisdiction. To the extent that Magnuson and related laws focus on domestic fishers to the exclusion of potential high seas foreign harvest in determining MSY and OY for straddling stocks, U.S. strategic decision-making is compromised. Likewise, the regulations promulgated pursuant to Magnuson are very squarely (and laudably) focused on adequate science for management planning and ecosystem modeling.\(^{69}\) But this too seems largely to the exclusion of also rigorously treating the substantial ecosystem impacts of human decision-making by large numbers of harvesters who are not subject to the U.S. legal regime. A game theoretic approach would force these sorts of absent considerations into the U.S. decision-making calculus.

Another example of counterproductive law is how the international legal regime can sometimes actually foster the free-rider problem. Consider a Regional Fisheries Management Organization (RFMO) created by 1995 UN Fish Stocks Agreement.\(^{70}\) After a group of RFMO members commit resources to programmatically rebuild an overexploited migratory stock, a prospective New Member approaches. The 1995 UN Agreement (Articles 8, 10 and 11) makes it clear that the “charter” members of a RFMO cannot bar prospective new entrants. This prospective member bore none of the costs, and would be receiving the benefits essentially for free, the essence of free-riding.\(^{71}\) Consistent with the “individual rationality constraint” demonstrated by game theory, this New Member free-riding problem could lead to legacy RFMO members to calculate that their expected cooperative payoffs would fall below their

\(^{68}\) 50 C.F.R. § 600.310(b)(2).
\(^{69}\) See, e.g., 50 C.F.R. § 600.315.
unilateral payoffs. These entities will either withdraw and return to unilateral action, or will not join to begin with.

One solution, of course, is to make new RFTO members buy their way in and pay their fair share of the investment. This would be in line with the policy recommendations above regarding user cost internalization and credible threats. But again, the individual rationality constraint means that each player will only cooperate if they can see more value from it vis-à-vis unilateral action, and there is no guarantee that this “price point” (the point up to which the new member will decide to buy in) will be sufficient to cover their purported “fair share.”

These are but two brief glimpses of what are probably many legal issues that can operate to hinder effective straddling stocks management. They are sophisticated and robust, but unfortunately cannot be given the attention they deserve in the narrower argument of this paper.

VII. CONCLUSION

Beyond the hard science of marine ecosystems and species population dynamics is something that has just as much impact on aggregate maximum sustainable harvest: strategic decision-making amongst rational self-interested actors. A good deal of fisheries resources consist of straddling stock, and therefore one of the central tasks of successful fisheries management is anticipating open-access dynamics outside of U.S. jurisdictional waters. Game theory, as the study of strategic behaviors by rational players, is an analytic tool almost perfectly adapted to this task of developing reliable, efficient, and successful international high seas or regional collaborations amongst competing entities.

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