Chapter 32
Opportunities in Social Science Research

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Abstract The opportunities for social science research change with developments in policy and social science, conservation biology, and ecological theory; population dynamics, quantitative methods, laws and current management or governance practices; industry operating procedures, social values, institutional change, and funding. This paper identifies opportunities for future social science research, and economics in particular, due to developments in economic theory and the shifting concerns of society. The opportunities lie in addressing the growing societal concerns over the environment, biodiversity, and sustainable resource use and bioeconomic modeling that begins to match advancements in population dynamics and ecology. The opportunities address multiple species, bioeconomic modeling that accounts for space, the heterogeneity of fishing industries and the need to address distributional issues and trade-offs. Future social science research will relate to impacts with different policies, incentives, and property and use rights, uncertainty, international management of transboundary stocks of fish and biodiversity conservation (whales, sea turtles, sea birds, dolphins, etc.), marine reserves, technical change, the shift in orientation from management of fisheries as a commercial fishery and a simple optimal harvest strategy to ecosystem management. Important ideas for the future include actual fisheries management of Pareto-improvements from a second-best situation rather than normative concerns that dominate most theoretical fisheries economics research.

32.1 Introduction

This chapter addresses opportunities for future social science research, and economics in particular, due to developments in economic theory, developments in other fields such as ecology and conservation biology, changes in fishing industries and social

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values, and changes in management measures. The perspective will be concerned first and foremost with what has resonated with the policy process rather than the different set of research objectives often addressed by academic economic research, which has its own, often independent and free-standing, set of objectives.

32.2 Economics

The economic analysis of fisheries as a field of serious study really began with the publication of what is still *the* seminal publication, that of Gordon (1954). Warming (1911) initially introduced the basic ideas discussed by Gordon (1954), but because Warming wrote in Danish, his ideas languished for many years well past Gordon's writing.) Close on the heels of Gordon followed the two publications by Scott (1955a, b). Gordon was mostly predictive or positive, providing a model of rent dissipation under open access and Scott was mostly normative, addressing how society should optimally manage renewable resources. These publications defined what remains the central thrust of fisheries economics, that there is: (1) an economic or Pareto optimum, what is commonly known as the maximum economic yield (MEY), and an opportunity cost to not achieving this optimum, and (2) the fundamental reason for the overfishing and overcapacity found in fisheries is what is now understood to be the absence of fully formed property rights, such as open access.

The first theme, which includes economic harvesting strategies, has had minimal impact in practice, although considerable time and effort has been spent in developing this theme, suggesting an over-allocation of scarce economics resources. (Portions of the discussion on economics, especially bioeconomics, build upon an excellent review of renewable resource economics by Deacon et al. (1998) and of fisheries economics by Wilen (2000)). The second theme of property rights and establishing proper incentives to guide fisher behavior and align private incentives with socially desirable goals has been very influential, and this influence continues to grow. This second theme has been the central contribution of fisheries economics to fisheries management, and its concepts and ideas have widely diffused to other social sciences, fisheries science, conservation biology and ecology, industry, governments, and international organizations, and are even starting to make inroads into the thinking of conservationists.

32.3 Bioeconomics and Economically Optimum Harvest Strategies

Fisheries economics has traditionally focused on normative economically optimum harvest strategies through static and dynamic analysis of the harvest of a renewable fish stock. Fisheries economics approaches the stock of fish as a stock of natural capital, and applies capital theory to the natural and man-made stocks of capital to obtain the economically optimum exploitation rates or harvests and the corresponding economically optimum stocks of the natural and man-made capital. (Capital is any good, asset, capable of yielding a stream of economic returns to society through time, in contrast to a consumption good or service.) Key early and fundamental literature includes Crutchfield and Zellner (1962), Plourde (1970), Clark and Munro (1975), Clark et al. (1979), Smith (1968, 1969), Turvey (1964). Wilen (1985) and Brown (2000) provide reviews.

Smith (1968, 1969) was one of the first economists to discuss the dynamics underlying the overexploitation of an open-access resource (with three behavioral restrictions for the interactions of the resource stock, individual firms, and industry), the application of phase diagrams from the field of differential equations, and the possibility of extinction along the adjustment path due to overshooting even though the stock equilibrium is positive. Wilen (1976) applied the dynamic model of Smith (1968, 1969) to the Pacific fur seal, showing that the sealing industry followed a pattern similar to that predicted by Smith. Berck and Perloff (1984) considered how potential entrants to an open-access fishery form their expectations determines the fishery's adjustment path to a steady state but not the steady-state values themselves; the paper contrasts myopic and rational expectations. Bjørndal and Conrad (1987) applied the model of Smith (1968) to examine stock extinction under open access using a non-linear deterministic model for the North Sea Herring fishery. Smith (1968), Gould (1972), Clark (1973), and Berck (1979) considered conditions for extinction of an animal population.

Optimum utilization of the fishery resources implies managing the resources in such a manner as to ensure that they provide the maximum flow of economic benefits to society through time. In principle, these economic benefits range beyond simply economic rents in the commercial fishery (rents are revenues less the costs of economic inputs) to include the benefits to society from conservation, biodiversity, and other non-market uses. The theory of resource economics rapidly expanded with the publication of Pontryagin's book on optimal control theory in 1962 (Pontryagin et al. 1962). These techniques were brought to the task of describing optimal use paths for both renewable and nonrenewable resources (Wilen 2000). The notion of a discount rate or a time value to benefits and costs received at different points in time by society was introduced in the process and is now widely used by population biologists.

In short, fisheries economics, beginning with Scott (1955a), has principally focused on the normative "first-best Pareto optimum" that comes from economically optimal exploitation or harvest rates, i.e., on maximizing economic rents through harvest rates under alternative conditions. The principal message has been that there is an economic optimum (rent maximization) and an economic opportunity cost (the foregone benefits from not adopting the next best alternative) to not following these economic harvest strategies, i.e., a focus on MSY or some other biological optimum does not fully yield the fullest economic benefits to society that are possible, such as with the Maximum Economic Yield (MEY).

The first message has largely been ignored in practice by policy-makers, and the scientific basis of harvest strategies has remained firmly in the hands of population dynamics. Real world economic considerations have little impact when quotas are set (Homans and Wilen 1997). Moreover, Wilen (2000, p. 323) observes:

> My assessment is that the profession has probably been too preoccupied with abstract, conceptual, and normative analysis. While these types of contributions seem to be rewarded within the incentive systems of academia, they have not played important direct roles in the policy process. It is certain that we have reached negative returns to further demonstrations that open access dissipate rents compared with various versions of optimized fisheries.

Deacon et al. (1998) reiterate this conclusion, and further observe (p. 392), as noted by Deacon et al. (1998, p. 390):

> In hindsight, elaborating the basic conditions for optimal dynamic resource use absorbed an enormous amount of intellectual effort for a payoff whose practical importance has been relatively small. In fisheries, managers are virtually never concerned with getting biomass stocks close to dynamically optimal long run levels. Instead, fisheries managers raise questions like: how will the industry be affected by trip limits, mesh size changes, or limit entry? How will bycatch and discards be affected and is the biomass safe from stock collapse? Significantly, many of these ‘management’ questions are predictive rather than normative and closer in spirit to Gordon’s focus. Ironically, they remain largely unanswered because economists chose to emphasize the optimization problem Scott posed instead.

Apparently, only in societies where the fishing sector provides an important contribution to gross domestic product and/or where property rights in fishing industries are more fully developed, such as with individual transferable quotas (ITQs), is much emphasis placed on economic rent. Otherwise, the policy emphasis tends to be placed on multiple objectives, including a biological optimum and social issues, such as employment and incomes, leading to optimum yield, and the distribution of costs and benefits in economically sub-optimum (second-best) allocations.

Bioeconomic models are the means by which economic harvest strategies have been analyzed. As a rule, single-species surplus production bioeconomic models based on Schaefer (1954) (that are sometimes more sophisticated in allowing for patchy resource environments, oceanographic dispersion of larvae, etc. as discussed below) form the workhorse bioeconomic model. Eggert (1998, p. 400) observes, “Analyzing the management of two or more competing species is more complex and, despite some progress, the single species approach still dominates the empirical work and simple stock-growth models are still practiced.” Some progress in accounting for multiple species (Conrad and Adu-Asamoah 1986, Flaaten 1988, 1991; Clark 1990; Placenti et al. 1992; Herrera 2006) has been made in this area within the Schaefer and analytical framework, but much more is required outside of this framework as in Kjærsgaard and Frost (2007). Quirk and Smith (1970) examined ecologically interdependent fisheries, comparing the open-access equilibrium with the social optimum. Hannesson (1983b) extended these results to examine if there is a price at which it is economically sensible to switch from exploiting the prey to the predator.

Although surplus production bioeconomic models based on Schaefer (1954) have served as the workhorse, some attention has been given to models (especially empirical ones) incorporating demographic information, principally year classes, based on Beverton and Holt (1957). In the words of Eggert (1998, p. 402):

> Dynamic optimization in the Beverton-Holt model quickly becomes complex and, including a stock–recruitment relationship, makes it almost incomprehensible from the dynamic viewpoint (Clark 1990). In empirical studies these problems are overcome by using some discrete instead of continuous variables, some strict assumptions are made, and optimization is solved by computer simulation (Hannesson 1993). The optimization problem is then to determine the efficient fishing mortality and mesh size, which depends on net growth rate and the real discount rate. In the simplest version, fishing mortality and cost per unit effort are assumed constant, but extensions are conveniently handled with a computer.

Steinshamn (1992) offers a comprehensive treatment of the Beverton-Holt model and Deacon (1989), Bjørndal and Brasãao (2006), and Kjærsgaard and Frost (2007) are excellent examples. Sumaila (1998b) uses a multicohort age-structured population model and a game theoretic framework in a predator–prey study. When year classes cannot be properly identified, another approach models growth according to the von Bertalanffy growth equation, such as Christensen and Vestergaard (1993) and Sparre and Vestergaard (1990).

Bioeconomic models have also always assumed time-invariant parameter values of the underlying growth functions except for an i.i.d. error term (Walters and Parma 1996; Castilho and Srinivasu 2005; Schlenker et al. 2007). Wilen (2004) and Schrank (2007) observe that fishing mortality is not likely to be constant, but is instead a function of economic and biological parameters. Schlenker et al. (2007) made innovative progress in allowing for cyclical growth parameters in both single and multispecies models. Neither optimal harvest rates nor optimal escapement remains constant as current bioeconomic models would predict. This approach shows that once the periodicity of the biological growth function is incorporated, many of the traditional policy prescriptions reverse. For example, periodic fluctuations in growth imply that it can be best to close a fishery during times when non-stationary biological growth parameters are improving most rapidly and the return from not fishing is highest (Schlenker et al. 2007).

A policy that derives the maximum sustainable harvest quota using the average growth rate will lead to overfishing and a crashing fish stock, as will an adaptive policy that utilizes a limited time-series of past data.

In sum, bioeconomic models have largely failed to keep pace with the very sophisticated and detailed population dynamics models that incorporate much more biological information, such as various forms of age-structured models and even more the modern synthetic models, time-varying biological parameters, and incorporation of uncertainty through Bayesian decision analysis (see Punt and Hilborn 1997). Nonetheless, for a countering view Hannesson (2007d, p. 699) recently observed:

> For stock assessment purposes, age-structured models are used for the Northeast Arctic cod. While more realistic, such models are also much more complex than aggregate biomass models. Furthermore, age-structured models introduce idiosyncratic elements of uncertainty, as parameters such as weight at age and natural mortality are not constant but variable and known only after the fact and with some uncertainty. The gains in validity from age structured models compared with aggregate biomass models will therefore be smaller than if their parameters were known with full certainty. This, and the fact that aggregate biomass models are computationally much simpler, is an argument for using them when they can be reconciled with reality.

Punt and Hilborn (1997) observe that the Bayesian approach to stock assessment determines the probabilities of alternative hypotheses using information for the stock in question and from inferences for other stocks/species. These probabilities are essential if the consequences of alternative management actions are to be evaluated through a decision analysis. Using the Bayesian approach to stock assessment and decision analysis it becomes possible to admit the full range of uncertainty and use the collective historical experience of fisheries science when estimating the consequences of proposed management actions. In the words of Wilen (2000, p. 320): "While biologists developed new and richer depictions of more realistic population processes with simulation modeling, calibration, and statistical estimation, techniques, economists mostly continued to work with simpler models that could be analytically solved."

Little has substantively changed since these words of Wilen were written. There has been progress in addressing patchy resource abundance, dispersal, and oceanographic linkages, which has been applied to address bioeconomics of marine reserves and spatial regulation in fisheries, often in a surplus production framework, but not always (Sanchirico and Wilen 1999, 2001, 2005; Smith and Wilen 2003; Holland 2003; Holland et al. 2004; Janmaat 2005; Schnier and Anderson 2006; Herrera 2006; Smith 2006a; Kjærsgaard and Frost 2007). Feedback rules have been considered (Grafton et al. 2000b; Steinshamn 2002). One major conclusion that falls out from this literature is that economic incentives determine both participation and location choices, so that fishing effort is not spatially uniform and that optimistic conclusions about reserves ignore economic behavior. The extent the conclusions from this discussion are actually implemented, are believed, or form the basis of actual policies may be limited by the chasm in modeling techniques between the fields of fisheries economics and population biology.

Despite the very real progress that has been made in broadening bioeconomic models, until these models build off current biological best-practice and shift from an emphasis on normative analytical solutions (which necessarily restrict the complexity of the model) to prediction and stochastic dynamic simulations, the economics discussion in this area will have difficulty in informing actual policy decisions (as opposed to an internal debate among economists). Computer-based simulations and more realistic assumptions will be central to progress in bioeconomic modeling, as in other branches of economics (Beinhocker 2006). Recognizing that the steady-state equilibrium is not at all steady due to technical change and incorporating technical change into bioeconomic models will also extend the usefulness of these models given the importance of technical change in the fishery economy (Squires and Vestergaard 2004, 2007). The incorporation of technical change, however, means that the steady-state equilibrium does not exist and will require shifting from the aesthetically pleasing phase diagrams and approach paths to a non-existent steady-state equilibrium to continual disequilibrium (Squires and Vestergaard 2007). Bioeconomic models founded on surplus production are simply inconsistent with the stock assessment advice given by population dynamics biologists. It is also unclear how interested policy makers actually are in normative economically optimum harvest strategies.

Policy-makers and different constituents in practice are very interested in the predictive and distributional impacts of policies, given TACs, from economists (and other social scientists). An assessment of distributional impacts in turn requires firm (vessel)-level models that recognize the heterogeneity of catch (multiple outputs) and effort (variable inputs such as fuel consumption, ice, crew, and fixed inputs such as the capital stock of vessel and some gear), gear types and vessel size classes, regions, and other factors that contribute to the heterogeneity in fisheries. Some important economic work has been conducted in this area (Weitzman 1974b, Johnson and Libecap 1982; Karpoff 1987; Boyce 1992).

Capturing such concerns over distributional impacts in a bioeconomic framework requires dynamic disaggregated models rather than highly aggregated ones, such as those developed by Brazee and Holland (1996), Smith and Wilen (2003), Holland (2003), Bjørndal and Brasãao (2006), and Kjærsgaard and Frost (2007). The latter is illustrative of what can be hoped for from such bioeconomic models in that effort is disaggregated, the population dynamics is age-structured rather than surplus production, considers recruitment and selectivity, and spawning stock biomass, allows discarding, species and inputs are multiple, fleets may be multiple, different areas can be fished, allows dynamic numerical allocation, and can perform both optimizations and feedback simulations. In fisheries that are managed by ITQs or other forms of rights-based management, a top-down, centralized economic modeling approach such as the workhorse surplus production bioeconomic framework does not address the issues of concern to the policy process. Dynamic bioeconomic mathematical programming models such as Bjørndal and Brasãao (2006) and Kjærsgaard and Frost (2007), and discussed further below, are very promising in this regard, but their accuracy (as with any model) always remains questionable given the complexity and difficulty of the task.

As with virtually all empirical production modeling (such as bioeconomics, production functions and frontiers, and fishing capacity), the current state of technology is taken as given, and the results reflect regulations, policy-induced technology that developed under regulation, and a property rights regime. The results may differ sharply from the technology that occurs after rationalization and also the change of technology that occurs over the normal course of events. (Homans and Wilen (1997) and Wilen (2007) essentially make this point.) The entire composition and types of fleets that would occur in a bioeconomic optimum might well differ from the model that is reflected in the data and conceptual framework. Also shared with most production modeling is a failure to address what is endogenous and what is exogenous; for example, "fishing effort" as a concept is an endogenous intermediate product which itself is a function of exogenous market prices and state of technology, but instead is typically specified as immune to changes in markets, technology, resource, and environmental conditions. (In fact, the issue is far more complex. Fishing effort is a composite input formed under very rigorous conditions, that of input separability (Hannesson 1983a, Squires 1987b) or a non-separable two-stage production process (Kirkley personal communication). [Au1]

Bioeconomic models typically abstract from decentralized markets and overlook the technical, and allocative inefficiency that occurs among multiple outputs and among multiple inputs and simply evaluates a form of scale efficiency, i.e., it simply looks for a 'sweet spot' (Squires and Vestergaard 2004, 2007). The maintained behavioral hypotheses and policy objectives also differ from those found in actual fisheries. By overlooking technical inefficiency (identified with skipper skill by Kirkley et al. 1998), the potentially critical role of the skipper and the fishing firm's management function in general is overlooked. Moreover, the empirical bioeconomic optimum should perhaps best be called the regulated bioeconomic optimum because it implicitly accepts the regulatory structure that is in place at the time that the data were generated (a problem shared with all production modeling and any equilibrium, whether temporary and short-term or very long-term). Bioeconomics, along with most production modeling, largely overlooks the pervasive uncertainty found in fishing industries. One of the principle results is suggesting that solving fishery problems is as simple as removing fishing effort rather than addressing the importance of incentives and property rights through production processes reflecting fleet heterogeneity, institutions, governance, and distributional impacts.

The research challenge that is relevant to actual policy-making, as opposed to a normative and conceptual approach, will require a predictive orientation and stochastic dynamic simulation or a framework that explicitly builds upon the current state of population biology, disaggregation in production and industry (i.e., catch, effort, vessels, and geography), acknowledging the growing importance of the ecosystem and biodiversity, allowing for time-varying biological growth parameters, addressing stochasticity (perhaps by Bayesian decision analysis) and recognizing the multiple objectives of policy-makers and stakeholders, distributional impacts, incentives, governance, and pervasive uncertainty.

Finally, one of the most critical areas for bioeconomic research lies in extending these models to integrate in situ environmental benefits of natural resource stocks into optimizing models of natural resource (Perrings et al. 1992; Li and Löfgren 1998; Deacon et al. 1998). Since harvesting can impair the ecosystem, say through gear damage of the benthic habitat or bycatch, and other non-market services, dynamic analysis of intertemporal resource allocation needs to broaden to recognize that the flow of ecosystem and environmental services and biodiversity conservation are determined simultaneously with the flow and stock of the resource. As a consequence, the impact of environmental considerations on the optimal extraction decision can be far more complex than simply determining the MEY. Deacon et al. (1998, p. 387) observe:

> The fundamental insight is that the flow of ecosystem and environmental services is determined simultaneously with the flow and stock of the resource. As a consequence, the impact of environmental considerations can be far more complex than making a dichotomous choice between conservation and extraction. Moreover, accounting for the complex dynamics of ecosystem services is likely to amplify the importance of flow considerations. … More generally, any environmental or ecosystem service provided by a natural resource stock can have important dynamic dimensions.

Li and Löfgren (1998) and Li et al. (2001) extend the basic bioeconnomic model to include non-market benefits from biodiversity conservation. An alternative approach, one that potentially serves as a rich source of research, is that by Finnoff and Tschirhart (2003).

32.4 Property Rights and Incentives

The second, and related, message from resource economics, one elegantly made by Warming (1911), Gordon (1954), and Scott (1955a, b), is that there is an enormous ecological and economic cost to society from open access, or more generally, from property rights that are not fully developed, and that property rights, markets, and other institutions coupled with public policies jointly create incentives (Grafton et al. 2006; Hilborn et al. 2005). The standard economic justification is that it facilitates the socially efficient exploitation of resources, enabling the owner (which may be an individual, group, or state) to exclude others from the resource and thereby internalize the externalities that would occur if access were free (de Meza and Gould 1992). The ability to exclude also provides incentives to invest in improving the quality of the resource and exploit at a socially optimum rate. Coase (1960) emphasized the importance of economic costs and discussed the distribution of property rights.

The importance and role of property rights is the key message that has soundly resonated with policy-makers, industry, environmental groups, ecologists, population biologists, conservation biologists, and others. Whole commercial fisheries economies in New Zealand, Iceland, and increasingly Australia, have been founded on rights-based management and represent the practical outcome of the concern with rights and incentives introduced by economics. In principle, economic incentives can be established through price controls (taxes and subsidies), quantity controls (quotas, rations), and property rights. The focus has largely rested on transferable shares of TACs or TAE, i.e., on transferable quantity controls upon which has been inferred a use right. Price controls have received little attention.

As a corollary, recognition is growing in fisheries, as well as other sectors of the economy and even globally, that traditional centralized “command-and-control” regulations, such as simple quantity controls on catch (trip limits) or fishing time (effort limits) can be counter-productive in achieving ecological and population objectives, much less economic ones. In the words of Wilen (2000, p. 309):

> One’s view of the solution should follow from one’s definition of the problem, of course, and from the start, economists viewed the policy problem differently from biologists, who defined the policy problem as one of excessive fishing mortality and hence one best addressed by reducing gear efficiency. Fisheries economists, in contrast, adopted Gordon’s view, which was that excess fishing mortality was just one of several *symptoms* of the fundamental problem, a lack of property rights.

As a further corollary, recognition is growing that the problem is far more than the symptoms of overcapitalization, excessive fishing effort, or overcapacity (depending on the modeling and conceptual framework used).

The critical advance in introducing property and use rights in fisheries, through Individual Transferable Quotas (1TQs), is due to Francis Christy (1973). Christy, in effect, adapted ideas from the environmental economics literature on individual rights-based solutions as a mechanism for solving pollution problems by Crocker (1966) and Dales (1968). Wilen (2000, ft 22, p. 317) states, “Probably the strongest proponents of ITQs during the late 1970s were Anthony Scott and Peter Pearse. Scott's interests in property rights solutions went back to his earliest writings on resources policy and related to his long-standing interest in institutions and their influence on resource use. Pearse had similar conceptual interests in property rights solutions but, in addition, an astute appreciation for the politics of resource policy implementation, developed on several commissions he headed on Canadian forestry and water policy" (see Pearse 1980, 1981). Subsequent social science research has further developed and evaluated individual property and use rights in both theory and practice. After recognizing the importance of individual rights, social science research began to evaluate different forms of property and use rights, most notably forms of common rights (Ostrom 1990; Baland and Platteau 1996; Bromley 1991). Nonetheless, property rights solutions, particularly ITQs, are not a panacea and are not necessarily the appropriate regulatory instrument in all instances (Squires et al. 1995).

Further work remains in the area of property rights, both as new forms of rights emerge and for formal analytical evaluation. A prime example is fishing cooperatives or voluntary agreements as a form of use right that is increasingly important as a type of rights-based management (Townsend 2005; Pinto da Silva and Kitts 2006). The initial work has largely been descriptive, although the Coasian framework of transactions costs has been recognized (Townsend 2005; Edwards 2008). More critically, initial work is underway applying ideas from industrial organization, contract theory, economic theory of teams, and voluntary agreements in environmental economics (Segerson and Miceli 1998). The second area of property rights research with promise is that introducing spatial dimensions to capture externalities with a spatial component, such as fish and larval movement. These forms of territorial rights include TURFs (Territorial Use Rights in Fisheries, introduced by Francis Christy 1982) and a close cousin, ITQs with a spatial dimension. Interest is growing in the community management system of Japan (Yamamoto 1995) and inshore waters of Chile (Gonzalez 1996), which has a spatial dimension. An emerging issue requiring research is the conflict between the implicit spatial rights inherent in ITQs and explicit spatial management, as for example in New Zealand (Bess and Rallapudi 2007).

The critical but usually overlooked issue with spatial rights, the collective action problem of actually managing the common property, is perhaps the most important area for research here. After all, the US EEZs managed by fishery management councils or the North Sea managed by the European Commission are both a form of spatial management that captures many of the externalities with an enormous spatial dimension. As territorial rights expand, a larger role will have to be made for civil society and without a market or other form of decentralized allocation and decision-making mechanism, the form of institutions to actually manage the right remain an open question. If society has claims through existence value and public goods, then society will have to participate in the decision making, which will not be left solely to industry or spatial rights holders or environmentalists. Lifting our eyes from spatial externalities to the governance and broader public good concerns is critical. Emerging partnerships or hybrids such as with The Nature Conservancy and ownership of rights along the Central California Coast may point the way forward and is one of the most important events unfolding worldwide in fisheries biodiversity conservation. There is likely a trade-off between the geographic limit of spatial rights and the collective action problem, i.e., with the institutions that are necessary to manage rights that encompass more than direct use values associated with catching fish but which now include public good issues such as biodiversity, ecosystem health, and existence of species. The issue is also far more than capturing spatial externalities in the ecosystem, since biodiversity and existence value issues are growing concerns of the entire population and the problem is managing a fishery for the entire society rather than as a form of harvest strategy for optimum yield. Then there remains the very practical but difficult problems of how to allocate and then to actually organize and govern the collective owners of the spatial rights.

Although ITQs are largely viewed as improving economic efficiency, the role of ITQs in the conservation of resources and the ecosystems that support them and the ensuring equity in the use of resources remain topics of controversy and research (Sumaila 1998a, Munro and Sutinen 2007).

Another area of research follows up on research by Gary Libecap (2006a, b) and elsewhere (Libecap 1989; Johnson and Libecap 1982) and looks at the law and economics of property rights in greater detail, applying contract theory, and draws lessons from the use of resources in other sectors of the economy. Yet another issue is aboriginal rights and their interface with the rest of the economy; examples are the Makah Indian tribe, Eskimos, and the bowhead whale, the Inuit, Maori, and Torres Straits Islanders.

The two fundamental ideas behind fisheries management until quite recently have been harvest strategies and biological optimums from population dynamics and rights-based management from economics. A third fundamental concept, developed largely by sociologists and anthropologists is that of co-management (see the writings of Pinkerton, McCay, Jentoft, Pomeroy, and others) but is not discussed in this essay.

32.5 Environmental and Public Economics

A fourth, and more recent concept behind fisheries management, comes from ecology, that of ecosystems management and the importance of biodiversity. Simply put, recognition has grown to the point where it is part of conventional wisdom that commercial fisheries are embedded in marine ecosystems and that the entire food web and ecological linkages, both abiotic and biotic, need to be considered to maintain healthy and resilient ecosystems and following from this, ecological and economically sound commercial fisheries. Ecosystems management of fisheries includes the needs of predators and dependent species in their food web. Economics increasingly views the ecosystem as natural capital (Heal 2007).

A corollary to ecosystems management and ecology has recently emerged, that of conservation and conservation biology. This field has emphasized the ecological and intrinsic importance of biodiversity and extinction. As with all forms of capital, when these two components of ecosystems interact, they provide a flow of ecosystem services. The ecosystem services are a return on the natural capital, that is, these services are the return that comes from investing in rebuilding this natural capital. Heal (2007, p. 14) observes, "This newly emerging area of environmental economicsis concerned with the identification and analysis and valuation of these ESS (ecosystem services). What are they? How do they affect human societies? How do the actions of human societies affect them? In short, what are the *values* arising from ESS and why should humankind care about these values?" In addition, viewing the ecosystem as natural capital yield a flow of ecosystem services analytically allow research using techniques that are well-established elsewhere in economics, including welfare economics and capital theory, and provides a natural means of collaboration between economists and ecologists (National Research Council 2005; Heal 2007).

The key policy recommendation from this school of thought for fisheries management has been that of marine protected areas and spatial management. Economists have turned some attention to marine reserves and spatial management, observing that fisher behavior, fishing capacity, and discounting the future cannot be ignored, as discussed elsewhere. The real challenge here will be in designing the institutions required to develop and manage marine reserves, evaluating their costs and benefits, compliance, and enforcement, and in dealing with the overcapacity issues that arise when existing vessels are simply shoved out of an existing area to make room for reserves. The problem is compounded since reserves are often implemented, like much of fisheries management, when the fishery is already overfished with overcapacity.

Another economic approach to ecosystems management is illustrated by Hannesson et al. (2007b), who evaluate the ecological and economic factors entailed in the conservation and management of the California sardine. This sardine, which eats zooplankton in the California Current, serves as both a forage fish for pinnepeds, sea birds, baleen whales, albacore tunas, salmon, and thresher sharks, and as a direct take for a commercial fishery. Hannesson et al. (2007b) evaluate the economic and ecological trade-offs arising from sardines as both a predator with direct commercial takes and as a prey for other species within an ecosystem model (Field et al. 2006) and subject to low frequency, climate-driven changes in ocean conditions attributed to long-term (inter-decadal) variability in reproductive success and survival. This coupling of economics and ecosystems modeling to address the economic value of a species as a commercial catch and as a forage fish and other ecosystems-based questions should provide a very promising topic for future research.

Matching or complementing the emergence of ecosystems management and conservation biology are the fields of environmental and public economics. Key concerns of environmental economics, in addition to ecosystems as natural capital, are that of external costs and benefits and measures of total economic value of ecosystems as natural capital and their services. External costs are those costs that are not accounted for by producers and consumers in markets and are sometimes called market failure. External costs neatly match with ecological and conservation concerns that are not accounted for by existing markets. Environmental economists have spent considerable time and effort on policy tools that correct for market failure, and these approaches have considerable promise to contribute to fisheries management dealing with conservation and ecosystems, such the work of Segerson (2007) on policy instruments to tackle incidental takes of sea turtles. The concept of total economic value emerging out of environmental economics recognizes that non-market values are important and often sizeable and should be counted in any assessments of costs and benefits when developing management strategies. Thus, for example, markets for fish typically only account for direct use values associated with the production and consumption of fish, but the non-market values are important, including indirect use value from ecosystem services and recreational fisheries and existence value from biodiversity. Thus, non-market values capture concerns emerging from ecology and conservation biology and the concept of total economic value is spreading well beyond economics to become a useful concept and part of the vocabulary of others. To contribute to the design and implementation of real-world policies for ecosystem management, economists must also produce quantitative measures of ecosystems as stocks of natural capital and flows of ecosystem services with non-market economic values that allow decision-makers to trade-off extractive and non-extractive values (Wilen 2004; Smith 2006b). Work in this area includes Barbier and Strand (1998), Brock and Xepapadeas (2003), and Tilman et al. (2005). See also Natural Resource Council (2005).

ITQs, while going far in addressing the resource stock externality, remain incomplete in this regard because they address the flow or catch and not the stock itself (Scott 1988). Even further, ITQs do not begin to adequately address the remaining external costs associated with ecosystems and biodiversity. Spatial or territorial rights are advocated to address these issues, but as discussed elsewhere, spatial rights do not fully capture all of the relevant external costs and face important collective action and compliance and enforcement problems, although their potential remains tantalizing. The concepts from environmental and public economics are useful in analyzing the remaining economic analysis required.

Public economics is concerned with, among other things, public goods and bads. Public goods are those goods and services that are non-rivalrous (non-depletable by the consumption of one economic agent and thus available to others) and non-excludable (so that consumption of the public good is available to all who wish). Impure public goods, also known as mixed goods, are goods with characteristics of both public goods and private goods (excludable and rivalrous). Protected species are no longer common resources because they are now non-rivalrous rather than rivalrous as with common resources (which are rivalrous and non-excludable). Thus sea turtles under the Endangered Species Act or cetaceans under the Marine Mammal Protection Act have features of public goods, but because they are sometimes also exploited, even if sometimes inadvertently as incidental takes, are also rivalrous and hence form impure public goods. Similar considerations apply to the great whales. Ecosystems services are often considered public goods.

Public economics is concerned with the demand and the supply of public goods, including investment to generate this supply, the decision-making process and how these goods fit into a market economy, and the free-riding that arises when all those who enjoy the benefits of public goods do not provide their share of the costs of investment in, and supply of, public goods and services. External costs and market failure are sometimes seen as arising from public bads (Kolstad 1999). In this light, the question of healthy ecosystems and biodiversity can be viewed as the supply of public goods (or bads) and the issue arises of how to fully account for the investment in these public goods and the demand by humans for these public goods and services.

Mechanism design is a potential area of fruitful research in its application to ecological public goods and their services. When collective decisions must be made, individuals' actual preferences are not publicly observable. Individuals must nonetheless be relied upon to reveal this information (Groves and Ledyard 1977). Mechanism design is how this information is elicited and the extent to which the information revelation problem constrains the ways in which social decisions respond to individual preferences. Mechanism design is a well-established area in public economics, but has yet to be applied to analyze fisheries and especially public goods such as ecosystems and their services.

32.6 Industrial Organization and Information Theory

Fishing industries, from the perspective of general economics, are simply industries comprised of individual firms that are usually producing multiple products (often different species) from multiple inputs using joint production processes (Squires 1986; Kirkley and Strand 1988). Their unique feature, of course, is the exploitation of a renewable resource stock. But many other industries are unique in some manner, so fishing industries should not be immune from standard tools of economic analysis of firms and the industries in which they function. Capturing the heterogeneity of firms (vessels) and recognizing that a steady-state equilibrium and very long-term analysis is simply a normative concept that is conditional upon the states of technology and the environment further reinforces the importance of recognizing that fisheries are indeed industries, conditional upon levels of resource abundance and technology. Although the analysis may be limited to static rather than dynamic considerations, important insights into actual regulation and industry functioning will be gained.

Analyzing an industry comprised of individual multiproduct firms leads to the economics discipline of industrial organization and the recognition of the complexity and heterogeneity of fishing industries passed over by the focus on harvest strategies and aggregate inputs, outputs, and harvest technology. Industrial organization, along with the introduction of game theory as an analytical approach and a means of evaluating strategic interactions of firms and even nations, and the topic of contract theory, are one of the most promising and critical areas of economic research in addition to property rights. This approach also fits with the policy-making process that is seldom focused on some conceptual steady-state economic equilibrium, but is rather concerned with an ever-changing environment and market economy where information is limited and asymmetrically held by different parties, and uncertainty prevails, and industries are comprised of multiproduct firms with complex bundles of multiple inputs.

Early attempts in this area have largely been static and building off of the multiproduct analytical framework of Baumol et al. (1982) (Squires 1986, 1988; Kirkley and Strand 1988; Salvanes and Squires 1995; Weninger 1998; Lipton and Strand 1989, 1992) and limited to the application of static production economics to fishing vessels as multiproduct firms in a competitive industry. Such a static approach takes the resource stock as given and overlooks strategic behavior, changes in technology and the environment, and the spatial dimension. Disaggregation of fishing effort into individual inputs, such as capital, labor, and fuel, disaggregation of catch into individual species, and disaggregation of the aggregate production function into the individual production relations for individual firms precludes ready incorporation of biological growth processes into applications of industrial organization models and analysis of individual firms, where these applications have the analytical solutions that economists dearly love. As with future meaningful bioeconomic analysis that incorporates realistic and relevant biological relationships, meaningful, and relevant industrial organization models that incorporate biological growth functions and other biological information will necessarily have to move to simulation and away from analytical solutions.

More recent work in applying industrial organization and contract theory to fishing industries has recognized that that there is an asymmetric information issue, one of moral hazard, between the regulator (principal) and the vessels (agents). (Asymmetric information occurs when one party to a transaction has more or better information than the other party. Moral hazard refers to a problem of asymmetric information whereby the actions of one party to a transaction are unobservable. This information problem arises because the fishery manager does not have complete information about all variables relevant for regulation. Hence, the regulator cannot easily and at low cost monitor fisher behavior.)

Adverse selection problems, another form of asymmetric information, can also arise. (Adverse selection arises when an informed individual's trading decisions depend on that individual's privately held information in a manner that adversely affects uninformed market participants. In adverse selection models the ignorant party lacks information while negotiating an agreed understanding of or contract to the transaction, whereas in moral hazard theory the ignorant party lacks information about performance of the agreed-upon transaction or lacks the ability to retaliate for a breach of the agreement.) In a vessel-buyback market, for example, an individual is more likely to decide to sell his or her vessel when that owner knows that the vessel is not very good (Groves and Squires 2007). When adverse selection is present, uninformed traders, such as buyback agencies, may be more wary of any informed trader wishing to sell and the agency's willingness to pay for the vessel or permit offered may be lowered.

The area of asymmetric information can shed light on how fishing vessels respond to regulations and how to better design regulations in this regard. (In economics, the problem of motivating one party to act on behalf of another is known as ‘the principal-agent problem.’ The principal-agent problem arises when a principal compensates an agency for performing certain acts that are useful to the principal and costly to the agent, and where there are elements of the performance that are costly to observe. The solution to this information problem is to ensure the provision of appropriate incentives so agents act in the way principals wish.) Considerable work in this area has been accomplished in standard industrial organization economics, but fisheries economists have barely scratched the surface. Some of this work in fisheries has been fundamentally qualitative (Salvanes and Squires 1995; Squires et al. 2002; Kirkley et al. 2003; Ahmed et al. 2007), but increasingly, formal static and dynamic models are emerging centered around the work of Frank Jensen and Niels Vestergaard (Jensen and Vestergaard 2000, 2001, 2002a, b, c, 2008); see also Bergland and Pedersen (1997) and Herrera (2004). Homans and Wilen (1997) recognized the role of the regulator and the endogeneity of regulations, but overlooked the asymmetric information problem and contract theory in general, and extensions of their early insights to account for these would enhance their approach.

A contract is an agreement about behavior that is intended to be enforced, whether external enforcement or through self-enforcement. Contractual relationships occur between two or more economic agents, including fishers and regulators, if the parties, with some deliberation work together to set the terms of their relationship. Contract theory is an important part of the regulatory problem that has not received attention in fisheries economics (important exceptions include Cheung 1970 and Johnson and Libecap 1982), but is important because many of the formal and informal transactions and regulations in domestic and international fisheries can be examined from this perspective. Contract theory can be applied to analyze enforcement and regulatory compliance and the entire regulatory approach. Applications of contract theory should be one of the most promising areas of research. One application that comes to mind is to extend the work of Homans and Wilen (1997) in this direction.

The microeconomic theory of quotas, rations, and other quantity controls, including ITQs and ITEs (both of which are also forms of use rights) and limits on gear, fishing time, and vessel size, can be further applied to better understand their impact on fishing firms and their behavior. Moloney and Pearse (1979) and later Arnason (1990) and Boyce (1992) examined ITQs in a formal bioeconomic framework. The microeconomic theory of rationing and quotas for firms, which was initially developed in consumer theory (Neary and Roberts 1980) and international trade (Neary 1985), provides such as basis and was further developed for individual firms in an ex ante context by Fulginiti and Perrin (1993) and Squires (1994) and extended to production quotas by Squires and Kirkley (1991) and Segerson and Squires (1993) and to ITQs by Squires and Kirkley (1995, 1996) and Vestergaard (1999), with further developments by Vestergaard et al. (2005) and Hatcher (2005). Extending Neary (1985), Squires (2007) developed an ex post approach entailing virtual quantities, the dual to virtual prices (used in the ex ante approach), which can be applied to evaluate the effects of changes in existing quotas. The microeconomic theory of rationing and quotas has also been applied to address the substitution of unregulated inputs for regulated inputs in input-regulated fisheries (Wilen 1979; Squires 1986, 1994, 2007; Dupont 1991) and to the spillover effects between ITQ-regulated species and unregulated species (Asche et al. 2007). Boyce (2004), Heaps (2003), and Weitzman (2002) took a slightly different track. Potential research topics include fractional ITQs on either target species or bycatch, especially for the latter when bycatch, such as sea turtles, are rare events (see Haraden et al. 2004; Hannesson 2008, Bisack and Sutinen 2006). Little is known about ITQs or ITEs under uncertainty.

Formal modeling of ITEs has yet to be conducted. Important research questions include conditions under which ITEs are the preferable form of property right (e.g., some circumstances such as compliance and enforcement by Vessel Monitoring Systems as in the Western and Central Pacific), effects of continual productivity growth, substitution between the regulated components of the fictional fishing effort, such as days fished, and the unregulated inputs, and linkages between fishing effort and catch.

An important but under-researched research topic on quantity controls, or market- based instruments in general, is an assessment of actual markets for transferable quantity controls, including ITQs and vessel licenses. How competitive are such markets and do they convey the appropriate price signals? Batstone and Sharp (2003), investigating the relationship between fishing quota sale and lease prices and total allowable catch for the New Zealand red snapper fishery, found support for the relationship proposed by Arnason (1990), who observed that under the assumption of competitive markets, monitoring the effect of changing the TAC on quota prices could be used to determine the optimal TAC. Karpoff (1984a, b, 1985) and Huppert et al. (1996) examined the relationship between license prices and fishery rents in Alaska salmon fisheries. Newell et al. (2005, 2007) empirically addressed this issue for New Zealand ITQ markets – the most comprehensive dataset gathered to date for the largest system of its kind in the world, considered both permanent sales of quota and lease markets. Newell et al. (2005) investigated asset and lease markets separately and found that market activity appears sufficiently high to support a reasonably competitive market for most of the major quota species, that price dispersion decreased over time, evidence of economically rational behavior in each of the quota markets, and an increase in quota asset prices, consistent with increased profitability. Newell et al. (2007) found that quota asset prices were related to contemporaneous lease prices in the expected way, that stocks with higher growth rates of fish output prices tend to have higher quota asset prices, and that the New Zealand quota system as a whole has functioned reasonably well and the prices at which quota have sold appear to reflect expectations about future returns on specific fish stocks. Further research in this area in well-established markets is necessary to generalize these results and provide further evidence on the workings of ITQ programs.

Pigouvian taxes directly address the resource stock externality but have largely been passed over by economists in favor of rights-based management based on transferable quotas. Yet, recent and highly imaginative analyses suggest that the fisheries economics profession may still have more to learn about this subject (Rosenman 1986; Sanchirico and Wilen 2001; Weitzman 2002; Jensen and Vestergaard 2008). Jensen (2008) observes that a study of taxes versus ITQs under conditions of price uncertainty and asymmetric information about costs is a promising research area.

Wilen (2000) made an observation that still rings true, that little is known about the actual investment process and how investment responds to regulations, technical change, profits, property rights regimes, and the like. The literature on economic capacity utilization in fisheries, beginning with Squires (1987), Segerson and Squires (1990, 1993), Squires and Kirkley (1991, 1996), Weninger and Just (1996), and Vestergaard et al. (2005); Hannesson (1996), Jensen (1990), Bjørndal and Conrad (1987) examining different capital adjustment functions; and Weninger and McConnell (2000) using a Cournot-Nash framework starts in this direction, but the role of uncertainty, alternative expectations about possible future earnings, options, and many other factors remains insufficiently explored. Investment in an abstract, normative, and dynamic context in steady-state equilibrium was considered by Clark et al. (1979) and Boyce (1995). Lane (1988), using a panel of micro-level data on vessel upgrades gathered from accounting firms serving fishers, found that vessel investments were heterogeneous, discrete, and lumpy and not easily aggregated. Taking a different tack, Homans and Wilen (1997) assumed instantaneous rent dissipation or fast dynamics for the entry and exit of fishing capacity. Since entry and exit are often slow and include investment and/or disinvestment (either in vessels or even in gear and electronics such as embodied technical change), their model can be extended in this direction.

The concept of fishing capacity (FAO 1998; Kirkley and Squires 1999), an application of Johansen's (1968) plant capacity has loudly failed to resonate with many academic fishery economists (Andersen 2007; Wilen 2007), but has struck a resonant chord with policy makers and applied economists because of its ease of application and understanding, availability of data, use of TACs from population biologists, and emphasis on vessels (firms) rather than an aggregate industry approach, use of a multiple-input technology with capital and variable inputs or fishing time (effort), consistency with the approach to capacity in the general macroeconomy and microeconomic theory, and most critically, the need for these types of quantitative measures that arises in the policy environment that can be used with TACs. In fact, measures of fishing capacity are one of the few quantitative products of economics actually desired by policy-makers and bureaucracies, precisely because it addresses the type of issues of concern for policy. The outcome is a moving target, which requires re-estimation on a regular basis, but policy-makers, stakeholders, and population biologists all understand that, like TACs, continual updating is required in an ever-changing, stochastic environment that is seldom, if ever, in a long-term, steady-state economic equilibrium. But without a scientifically rigorous approach to providing such an assessment, policy discussion and hard choices often grind to a halt. Policy makers and industry, if not the modelers, understand that economic and population models are simply models. As with all production models, including bioeconomic, the results are limited by conditioning upon the current state of technology, fleet configuration, regulatory conditions, existing data, and other factors discussed above. Current research includes evaluation with multiple objectives (Kjærsgaard 2007), undesirable outputs such as bycatch (Scott et al. 2008), which can include using directional distance functions to account for the undesirable outputs, and two-stage models in which optimum fleet size and structure is found (Kerstens et al. 2006; Scott et al. 2007).

32.7 Productivity Growth and Technical Change

Technical change has dramatically transformed virtually all industries, and fishing industries are no exception. Growth in productivity (or fishing power as it is called in the general fisheries literature), including technical change, is one of the most important areas for future research in fisheries economics, and may well be the single biggest contributor to the increases in fishing capacity and mortality that threaten many fishing industries. Productivity growth is comprised of many contributing components, including technical change, changes in technical efficiency, and changes in capacity utilization.

Beginning with the path-breaking paper by Hannesson (1983a) for a deterministic production frontier, an extension by Kirkley et al. (1995) for a stochastic production frontier, and Salvanes and Steen (1994) using the thick frontier approach, a veritable cottage industry has emerged that has analyzed (output-oriented) technical efficiency, and found a wide range of efficiencies. (Beginning with Kirkley et al. (1998), technical efficiency was also linked to skipper skill.) Squires (1987c), Segerson and Squires (1990, 1993), Weninger and Just (1996), Kirkley and Squires (1999), and Vestergaard et al. (2005) extended the economic theory of capacity and capacity utilization to fisheries. Earlier, a substantial literature arose in fisheries economics defining fishing capacity in terms of a maximum potential fishing effort that is then applied to the resource stock to produce a flow from the resource stock, i.e., the catch. This literature differs considerably from the microeconomic theory of capacity that is applied to all other industries (as expounded in Klein 1960; Morrison 1995).

Squires (1992) demonstrated that productivity growth must be separated from changes in the resource stock and extended standard analysis to renewable resource industries. Jin et al. (1992), Fox et al. (2003), and Hannesson (2007c) extended the measurement of productivity growth to profitability of a fishery and to overall fisheries in an economy using aggregate data and when new fisheries or products develop. Squires and Reid (2001), Felthoven and Paul (2004) and Squires et al. (2008) extended productivity growth to account for changes in the environment. Tara Scott is researching productivity growth when there are undesirable outputs and rare events, such as incidental takes and mortality of cetaceans, sea turtles, and pinnipeds in the California drift gillnet fishery. Ample scope exists for further methodological and empirical work on the measurement of productivity growth, including decompositions of productivity growth, inclusion of undesirable outputs, accounting for the state of the environment and resource stocks, different index number, and functional forms. Evidence is only now beginning to accumulate on actual rates of productivity growth in various fisheries.

Parallel to the economic analysis of productivity growth has been a steady series of studies on the growth in fishing power in the biological literature. Critically, population assessments involving the more disaggregated synthetic models often specify an assumed rate of growth in fishing power. (Comparably, macroeconomic models of climate change adopt a similar approach.)

The key problem for both economists and biologists remains distinguishing changes in productivity (and especially changes in technology) from changes in the resource stocks and the state of the environment (e.g., changes in temperature, thermoclines, etc.). No research has yet attempted to account for changes in ecosystem services as an outcome. Both economists and biologists largely rely on catch per unit effort-landings data for their source of information, and these data are confounded by all of these sources of variation. Fishery-independent data on biomass are important, and even stock assessments from fishery-dependent and other data are critical because of the exogenous information that is introduced (such as information on age structure, gender, length-weight and length-age, and recruitment) that helps to militate against the simultaneous bias and exogeneity statistical problems that otherwise emerge.

Remarkably little research has been conducted on the single biggest contributor to growth in productivity and fishing capacity, technical change. (Technical change can be classified as a product or process innovation, where product innovation or the creation of new products is far less important than process innovation in fish harvesting, which is concerned with new ways of producing existing products.) Remarkably, virtually all of natural resource economics has overlooked one of the most important driving forces in economic growth, technical change. In a positive framework, Squires and Grafton (2000) conducted the first formal econometric study of technical change in fishing industry. Kirkley et al. (2004) examined embodied technical change in fisheries. Jensen (2007) examined the impact of cell phones on artisanal fisheries in Kerala, India. Hannesson et al. (2007a) examined technical change in the Lofoten cod fishery of Norway and Gilbert et al. (2007) examined technical change in a Malaysian artisanal fishery. Squires (2007) examined technical change in a Malaysian purse seine fishery, finding that process innovations increased trip-level profits. Squires et al. (2008) measured the rate of exogenous technical progress and its diffusion in the Korean purse seine fleet for tunas in the Western and Central Pacific, but did not address more sophisticated rates of diffusion. Econometric studies can specify technical change as smooth and exponentially growing over time by using a time trend, but if there is panel data, then consideration can be given to the approach of Baltagi and Griffin (1988) that allows rates of technical change that are not smooth and exponential. Key empirical research questions include which type of innovations are adopted and why and by whom, their rates of diffusion, their impacts on input and output use and profits, their impact on catch per unit of effort, the catchability coefficient, overall resource abundance, site location, trip length, crew size, etc.

Research is only now beginning on technical change in a normative, bioeconomic framework. Murray (2005, 2006, 2007) examined the manner in which technical change can lead to stock collapse, which is a critical but vastly under-appreciated source of fishing mortality and capacity growth. Murray (2006) showed that technological change can lead to overestimation of natural growth in stock assessments. Squires and Vestergaard (2004, 2007) introduced exogenous technical change and exogenous and endogenous technical efficiency into the standard Gordon-Schaefer bioeconomic model. In the static model, they found that technical progress leaves maximum sustainable yield and the corresponding resource stock level unaffected but reduces the required effort to reach this point. Technical progress always reduces the static and dynamic open-access and Pareto optimum resource stock levels, at any level of fishing effort and resource stock, but only increases equilibrium sustainable yield for effort levels less than maximum sustainable yield; essentially, technical progress only expands sustainable yield when the marginal product of effort is positive. Technical progress increase rents up to the static open-access equilibrium level of effort. At the static Pareto optimum, technical progress reduces the effort required to reach the efficient scale of production. In a dynamic model, they developed a modified Golden Rule with technical change, in which there is a new term added beyond the marginal productivity of the resource and the marginal stock effect compared to the traditional rule, namely the marginal technical change and technical inefficiency effect. This term is positive, so that with technical change – all other things equal – the stock level is higher compared to the situation without technical change, beyond the marginal stock effect. However, over time the effect of technical progress will lead to lower stock levels, because the unit profit of harvest increases, meaning that the effect of these terms decline over time. They further found that in a dynamic context there is no longer a steady-state equilibrium. The effect of technical change is that the optimal level of the stock declines over time, because the unit profit increases due to technical progress. However, the short run effects of introducing technical progress is an increase in the stock size. In addition, technical progress after time sufficiently lowers costs to counterbalance the marginal stock effect in a stationary solution without technical progress. Technical change can lower the resource stock and there are not substitution possibilities between the resource stock, man-made capital, and technical progress in stock-flow production processes.

Most technology is actually embodied in the capital stock and in new investment in capital equipment particularly. However, little research in fisheries other than Kirkley et al. (2004) has been done specifying technical change as embodied rather than disembodied.

The relationship between exogenous technological change and extinction for pure compensation growth functions has been addressed in bioeconomic models by Murray (2007) through simulation and Squires and Vestergaard (2007) analytically, but has yet to be considered when there are Allee effects or more sophisticated forms of population dynamics, such as depensation or age-structured growth, or endogenous technological change.

The (Hicksian) biases in input usage and outputs (species) due to exogenous technical change have yet to be examined (and cannot be until fishing effort is disaggregated into individual inputs and total catch is disaggregated into individual outputs or species), although current work by Gillbert et al. (2007) is addressing this issue. Estimation of welfare gains (including all sources of total economic value) and rates of return from technical change, say in response to conservation requirements, has yet to be considered. Changes in property rights and regulatory regimes can be expected to generate input and output biases and alter the rates of substitution and product transformation, adoption, and diffusion.

Research on technical change has largely focused on target species or desirable outputs, but an important area of research is on reducing bycatch of undesirable outputs. Technical change research can also examine the impact of biotechnology and breeding through their impact on the intrinsic rate of growth and age structure of the population (McAusland 2005). The inter-relation between technical progress in the fisheries sector and the rest of the economy has yet to be examined, although recent but very limited progress has been made (Hannesson 2007c, Hannesson et al. 2007a).

Endogenous technical change is also important and has received no attention in the fisheries economics literature. What is unknown is the extent to which different property right regimes, regulations, market conditions, and other policies influence the development of new technology its rate of adoption and diffusion, and choice of technology to adopt. (Diffusion refers to the process by which a new technology gradually penetrates the relevant market.) Learning by doing (an alternative to modeling endogenous technical change as a function of research and development), such as the development of the back-down procedure to minimize dolphin mortality when harvesting tunas, is a very important part of the endogenous technological response to conservation issues, but has yet to be considered. What are the causal factors leading to learning by doing and how are costs lowered? There is no opportunity cost from learning by doing other than the cost of current production (since there is no crowding out of alternative research that might have been undertaken such as with research and development), which affects how this research will be conducted. A key challenge for research on learning by doing is disentangling the causal factors that lower costs (Pizer and Popp 2007). The statistical correlation between experience and lower costs is strong, but understanding the causes of cost reductions is necessary for policy decisions. Disentangling the various learning mechanisms is difficult and learning by doing can be confounded by research and development, which is often poorly measured even in research outside of fisheries.

Some new ideas – endogenous technical change – are developed through formal research and development (demand-pull responds to the market and technology-push responds to scientific advances), such as sonar to detect species composition below fishing aggregator devices in purse seine fisheries for tropical tunas. Studies could analyze the economic returns to private research and development, recognizing that knowledge spillovers result in a wedge between private and social rates of return, but the gap can be narrowed when such research is government financed. There is an opportunity cost to research and development from crowding out alternative research and this additional social cost needs to be considered. This wedge between private and social rates of return suggests that firms or even nations ignore potentially profitable technological developments since they are not able to capture a large share of the benefits to their research (which forms a public good). There is little or no evidence on returns to research and development, either private or government. Empirical evidence on private research and development is hampered by the lack of data that is not proprietary and on public research and development by the very nature of government projects, which are often more basic and long term.

A related question that arises is what is the optimal level of research and development for new technology to address ecosystem and biodiversity externalities, recognizing that due to the wedge between private and social returns that the existing level is likely to be suboptimal. The presence of two externalities complicates the matter and leads to second-best situations. This problem is aggravated for transboundary environmental issues, regardless of whether research is funded privately or by governments due to the transboundary externality and multiple governments, and the consequent creation of a second-best situation of two or more externalities (the transboundary one, the one arising from private and public good aspects of research, and in some instances the one arising from ill-structured property rights). Moreover, simply subsidizing new research and development may be insufficient and concern may need to be given to policies required for adoption of these technologies where resistance can sometimes be high. There is a growing body of empirical literature that links environmental policy to innovation in areas outside of the ocean (Pizer and Popp 2007). Most of these studies have focused on estimating the direction or magnitude of the relationship between policy and innovation (and use patent data). Since research on fisheries issues has not even begun to think about this topic, considerable opportunity may exist for future and important research.

Pizer and Popp (2007, p. 17) observe:

> In addition to correcting for underinvestment by private firms, many government research and development projects aim to improve commercialization of new technologies (or "transfer" from basic to applied research). Such projects typically combine basic and applied research and often are government/industry partnerships (National Science Board 2006). … As such, this technology transfer can be seen as a step between the processes of invention and innovation.

This aspect of the development and diffusion of new technology has also yet to be researched in fisheries economics.

Endogenous technological change can also be classified as short- or long-term. For example, considerable technological change is in response to conservation and sustainability issues that are fairly immediate in nature, such as the development of turtle excluder devices or the replacement of circle hooks by J hooks in shallow set pelagic longline fisheries or the back-down procedure or Medina panel to reduce dolphin mortality in purse seine tuna fisheries. Other forms of technological change are longer term in nature and represent not process innovations to an existing production process as represented by the gear in use, but the introduction of an entirely new production process. New methods of fishing are one example, such as the development of trawl gear or fishing aggregator devices coupled with GPS, radio beacons, and sonar designed to determine the species composition below the fishing aggregator devices.

Diffusion of new technologies in fishing industries has barely been considered, with Squires et al. (2008) the only known study beginning to address the issue, although they only begin to scratch the surface. What are the factors that influence the rate of diffusion and the lag in general between invention and adoption? Many of the new technologies of importance to public policy are related to conservation and their diffusion is affected by public policy, such as various methods of reduce dolphin, sea bird, and sea turtle mortality, the use of pingers to reduce whale interactions on drift gill nets, or trawl mesh size and design research. Some technologies, such as floating aggregator devices, diffuse through fleets at different rates, with some skippers who are early adopters and other skippers adopting later. This diffusion even varies by national fleets with tropical tunas and purse seine vessels. Little is known about the rates of diffusion and its causal factors. For example, fishing aggregator devices appear to surpass competing technologies of finding tunas through schools in performance and cost, but are not immediately chosen, in part due to higher prices for the larger yellowfin tunas found in schools but also due to general fishing practices built up over time. Is this slow diffusion a result of rational choices responding to various incentives, market inefficiencies, or other factors?

The diffusion of new technologies takes time, which varies by the situation. Adoption of a new technology typically begins with a limited number of early adopters, followed by a period of more rapid adoption, in turn followed by a leveling off of the rate of adoption after most have adopted the technology. This process generates the well-known S-shaped diffusion curve: the rate of adoption rises slowly at first, speeds up, and then levels off as market saturation approaches (Pizer and Popp 2007). Pizer and Popp (2007, p. 19) observe:

> Early attempts to explain this process focused on the spread of information (e.g., epidemic models, such as Griliches [1957]) and differences among firms (e.g., probit models, such as David [1969]). In fisheries, Gilbert et al. (2007) examined technology adoption through a probit model. More recently, researchers combined these explanations while adding potential strategic decisions of firms. These papers find that firm-specific differences explain most variation in adoption rates, suggesting that gradual diffusion is a rational process in response to varying incentives faced by individual actors.

Pizer and Popp (2007) further note that environmental technologies can differ from many other technologies due to regulations, and that regulations dominate all firm-specific factors affecting the diffusion of such environmental technologies in the few empirical studies conducted in this field. Similar results, in which environmental regulations increase the probability of adopting environmentally friendly technologies, can be expected for endogenous technical change related to conservation, but not necessarily for commercial innovations such as fishing aggregator devices in the Western and Central Pacific Ocean, although to some degree regulations from dolphin conservation may have affected the deployment of such innovations in the Eastern Pacific Ocean. In contrast, innovations in response to expected permanent changes in market conditions, such as long-term increases in fuel prices or rising ex-vessel prices for some species from increasing scarcity, may be adopted more slowly, as it is cost savings, rather than a direct regulatory requirement, that matter. Innovations in fishing industries, whether in response to changes in conservation or market forces, can be expected to face the issue of diffusion across regions and nations when there are transboundary resources and transnational fishing fleets involved (see Keller 2004 for other industries).

[Au2] Induced technical change has yet to be considered (see Ruttan 2000; Thirtle and Ruttan). Constraints on public bads or undesirable outputs, such as bycatches of dolphins or turtles, create shadow prices. In output space, the ratio between the price of the private good or desirable output and the public bad or undesirable output alters and the fishing firm reduces its scale of production. Over the longer term, investment can change and even further, the change in product prices can induce technological change that shifts the production possibility frontier and is public bad-saving in its Hicksian bias.

Further research on technical change is one of the single most critical areas of research in fisheries economics because of the transformative power of technical change on the very nature of industries, the role of technical change as a key response to conservation needs, and the contribution of technical change to the growth in overcapacity, overfishing, and overfished resource stocks and depleted ecosystems. Much technological change, such as some forms of the electronics used on vessels to find fish, is exogenous to the fishery sector.

32.8 Mathematical Programming Models

Mathematical programming models, using linear, nonlinear, multi-objective, goal, and other approaches, may be among the most useful lines of research that provides policy makers what they tend to want. Specifically, such models are heterogeneous in vessels, regions, gears, and other defining factors, can incorporate age-structured population dynamics, recruitment, and selectivity, specify multiple outputs and multiple inputs, allow multiple objectives rather than a simply economically expedient objective function, and allow evaluating inter-temporal and intra-temporal policy trade-offs. As with all empirical production models, including bioeconomic and microeconomic production functions, the results are conditional upon the regulatory structure, data, fleet configuration, resource abundance, and technology, but these limitations cannot be overcome in empirical work and abstractions away from this simply lead to normative and conceptual models that are usually ignored by policy makers. Recent work in this area includes Enriquez-Andrade and Vaca-Rodriquez (2004), Mardle and Pascoe (1999, 2002), Kjærsgaard and Frost (2007). Some mathematical programming models are static (conditional upon the resource stock) and others are dynamic bioeconomic models. Kjærsgaard and Frost (2007) define the current research frontier and point the way for future applied research in multispecies, multiple inputs, and dynamic bioeconomic models with age-structured population dynamics, consideration of recruitment, selectivity, and spawning stock biomass. As they observe, the capital investment function requires further attention, allowing for trends in economic performance and stock levels, improved analyses regarding discards and selectivity, and incorporation of price and cost functions.

32.9 Technology Structure and Duality, Allocative and Technical Efficiency, Skipper Skill

Considerable intellectual effort has been allocated to this area of applied microeconomic research. This area of research focuses on individual vessels and a disaggregated production process that entails multiple inputs and outputs. This research area aims to better understand the harvesting process at the level of the individual vessel and is largely, although not entirely, empirical. Because this line of research deals with situations not normally assessed by standard microeconomics, it has also extended applied microeconomic theory in the area of rationing and quotas, capacity and capacity utilization, productivity growth, the multiproduct cost structure of firms from revenue and profit functions rather than directly from cost functions, and the individual firm's management. This line of research's principal message is that fishing industries are comprised of individual firms or vessels harvesting multiple outputs or species in a joint harvesting process and that, fisheries regulation that overlooks this central fact will be subject to under-performance.

Asche et al. (2005) and Jensen (2002) review dual approaches to modeling the harvesting technology. The dual approach is very suitable for providing knowledge of the disaggregated structure of production and costs based on a positive analysis and the theory of the firm (Asche et al. 2005). One of the questions of greatest interest addressed by the dual approach is the substitution between inputs in order to answer the question of how readily fishers can substitute between inputs in response to regulation. This is the question of the microeconomics of rationing and quotas discussed above, often loosely called "capital stuffing," which is addressed by the general model of input substitution under quantity controls by Squires (1994). Asche at al. (2005) and Jensen (2002) survey the numerous empirical studies of input substitution possibilities that use the dual approach. To date, although these studies have shed considerable light upon the structure of fishing technology, their impact upon policy has been negligible. Similar issues arise as with all production studies, as discussed elsewhere. The dual approach was used by Dupont (1990) to evaluate rent dissipation in a fishery. The dual approach has also been used to examine economic capacity utilization, with original extensions of the theory to profit maximization (Squires 1987a, Segerson and Squires 1993), revenue maximization (Segerson and Squires 1995), quotas and rations (Segerson and Squires 1993; Squires 1994), and multiple products (Segerson and Squires 1990). The dual approach has also been applied to examine the fishing vessel's multiproduct cost structure, with extensions of microeconomic theory to profit- and revenue-maximizing firms (Squires 1988; Squires and Kirkley 1991). The dual approach has also been applied to provide shadow prices for ITQs (Squires and Kirkley 1996; Dupont et al. 2005). The dual approach has also been applied to evaluate the multispecies issue, clarifying the issues of separability (conditions under which an aggregate input, fishing effort, and output, total catch) exist and joint and non-joint harvesting (Squires 1987; Kirkley and Strand 1988). An important but somewhat overlooked paper by Bjørndal (1987) develops an intertemporal profit function and examines the relationship between the optimal stock level and production technology. Extensions of this model represent an opportunity for further research. Additional research includes measuring potential resource rents under alternative regulatory regimes (Dupont 1991; Eggert and Tveterås 2007). Stephen Stohs is extending ration and quota theory from binding constraints with 100% probability to multiple binding constraints, each with an independent probability Poisson distribution because of count data, and collectively as a joint or combined probability with an associated distribution.

Considerable applied research has also been given to measures of (output-oriented) technical efficiency and skipper skill at the level of the individual vessel. Technical efficiency refers to the individual firm or vessel's level production given its bundle of inputs, such as vessel, gear and equipment, crew, fuel consumption, and states of technology, environment, and resource stocks, relative to the best-practice frontier established by the highest achieving firms or vessels. Hannesson (1983a) first measured technical efficiency through estimation of a deterministic production frontier, in which there is a one-sided deviation from an estimated frontier not accounting for stochastic disturbances; as with all deterministic frontiers, performance differences due to technical inefficiency and stochastic disturbances cannot be distinguished. Salvanes and Steen (1994) measured technical efficiency through estimation of a thick frontier, in which rather than allowing for a one-sided disturbance term to account for inefficiency, the best-practice frontier is determined, after estimation of a production function, by grouping together the vessels with the smallest disturbances. Kirkley et al. (1995) first measured the frontier through a stochastic production frontier, thereby allowing for a one-sided disturbance term to account for technical inefficiency or deviations from the best-practice frontier and a two-sided i.i.d. disturbance term to account for stochastic variation above and below the best-practice frontier due to luck, measurement error, random variation in weather, excluded variables, and other factors. Squires and Vestergaard (2007) introduced output-oriented technical inefficiency into the Gordon-Schaefer bioeconomic model.

Kirkley et al. (1998) observed that technical inefficiency corresponds to the fishing captain's management of the vessel or skipper skill, where according to the good captain hypothesis some skippers display superior skill in finding and catching fish and thereby establish the best-practice frontier. They also related skipper skill or technical efficiency to various potential explanatory variables, including institutional and measures of the captain's human capital. Squires and Kirkley (1999) allowed for technical inefficiency through panel data methods, specifically fixed and random effects, with a standard production function rather than a production frontier using a one-sided disturbance term. Grafton et al. (2000a) first accounted for economic inefficiency, including both technical and cost inefficiency, in a study of the impact of ITQs in the British Columbia fishery for Pacific halibut. Kuperan et al. (2002) reviewed the anthropological fisheries literature on skipper skill and related it to technical efficiency in a Malaysian trawl fishery. Subsequently, numerous empirical studies have appeared in this area for fisheries around the world, demonstrating various ranges of technical efficiency or skipper skill and often, although not always, sometimes finding that measures of the captain's human capital can in part explain variations in skipper skill from vessel to vessel and sometimes not finding any relationship at all. Considerable work has been conducted in this area by Sean Pascoe and colleagues and recent econometric advances by Flores-Lagunas et al. (2007), Holloway and Tomberlin (2006), and others.

Potential research topics include more sophisticated studies of economic efficiency, based on profit, revenue, or cost efficiency, further assessment of the factors determining efficiency differences among vessels and skippers, extending the sophistication of econometric approaches, and in general accumulating the empirically based knowledge of efficiency differences and skipper skill. Promising areas of current research include the application of directional distance functions to allow for undesirable outputs such as bycatch and the impact upon firm or vessel efficiency and skipper skill; for example, are there some skippers that are better skilled at avoiding bycatch while maintaining high levels of efficiency in their target catches?

32.10 Consumption, Demand, and Price Analysis

Consumers are invariably left out of the picture, since policy actions seldom have a measurable immediate impact upon them, although they do on producers and the environment. The ready availability of close substitutes and imports can make the impacts of policy actions on consumer welfare negligible. Industry and environmental groups largely influence regulatory institutions with minimal representation by consumers at best. An analysis of consumers and consumer benefits requires vastly more attention than is given to the analysis of demand, which is an area of fertile research largely untouched. Issues that arise here are how to obtain measures of consumer welfare (especially compensating and equivalent variation) at different levels of the retail chain ranging from ex-vessel to retail. Such measures are useful in benefit–cost analysis, which in fishing industries largely ignores consumer welfare and concentrates on producer welfare. Responsiveness of price to ex-vessel landings can also be evaluated from such studies. Some attention has been given to this area, but more is required (Barten and Bettendorf 1989; Asche 1997; Salvanes and DeVoretz 1997; Holt and Bishop 2002; Fousekis and Revell 2004; Park et al. 2004; Asche et al. 2001; Wessells et al. 1999). One of the key research issues is whether at the ex-vessel level price is a function of quantity, yielding an inverse demand function, or quantity is a function of price, yielding a direct demand function, or whether it varies by species, yielding a mixed demand function. Additional research includes proper specification of functional forms, index numbers and aggregation of species into composites to reduce the number of species in the demand functions to manageable numbers, and separability issues to distinguish among types of fish and even between fish and other substitutes in consumption.

Measures of economic welfare for consumers (consumer surplus, compensating, and equivalent variation) and producers (producer surplus, rent) are a core component to cost–benefit analyses. Welfare analyses are often required in the United States and elsewhere, but considerable scope remains for research in this area. Important research is emerging (Park et al. 2004; Bockstael and McConnell 2006).

Horizontal and vertical price linkages between markets are important areas of economic research. Beginning with the first study by Squires (1986), a plethora of research has examined the nature of horizontal and vertical price linkages using time series econometric techniques, including Granger causality and co-integration; much of this research has been centered on the work of Frank Asche. The policy implications of such research are not always clear, although they help consumer demand specification by clarifying the extent of the market. Some analyses have been extended to policy research, evaluating the impact of spatial price linkages on a revenue-sharing scheme in the US tuna fleet and clarifying that all Regional Fishery Management Organization areas for highly migratory species are linked by price, so that policy actions in one area affecting the volume of landings can reverberate throughout the world.

The impact of ecolabeling on demand and for conservation is an infant field of research (Gudmundsson andWessells 2000; Teisl et al. 2002). More research is justified in this area, including the relative costs and benefits for ecolabeling and certification of fisheries; the costs may outweigh the benefits in some smaller fisheries, especially artisanal ones.

32.11 Climate Change and Variation

Climate change and fisheries is emerging as an issue of growing importance. Climate change includes short-term, such as ENSO events, decadal, or medium-term, such as the Pacific Decadal Oscillation, and long-term, such as global warming. Biologists have established the importance of climate and the environment in general on abundance and catches, as for example in Pacific salmon and the PDO (Beamish and Bouillon 1993). Economists are beginning to address the impact of climate change on such issues as the change in harvesting strategies, fleet size, dynamics, and investment, risks of extinction, jurisdictional issues as fish stocks shift from one EEZ to another, variability in stocks and harvests, and other related issues (Costello et al. 1998; Dalton 2001; Hannesson et al. 2006; Sun et al. 2006; Herrick et al. 2007; Hannesson 2006, 2007a, b), and in 2007, special issues in *Marine Policy* and *Natural Resource Modeling*. Acidification of the ocean due to global warming and its economic impact upon fishing industries, biodiversity, and the ecosystem in general represents a potential research topic of growing importance. Nonetheless, there has been very little econometric work shedding light on the costs and benefits associated with different climates or on the costs of adjusting to different climate regimes. The damage function for climate change remains largely unknown. The role of technical change in adapting to climate change remains unexplored.

32.12 Economics of Transboundary Resources

Transboundary marine resources include global common resources, belonging to humanity as a whole, such as fish and sea turtles, and global public goods or bads, such as the protected great whales. Transboundary fish, such as highly migratory species including tunas, billfish, and oceanic sharks, and straddling stocks, such as coastal pelagics in Eastern Boundary Currents, are important in the international context. Multiple externalities arise in this context, including the transnational, "traditional" resource stock, and those related to public goods and common resources of biodiversity conservation and sustainable ecosystems.

Considerable modeling and empirical research, usually in a surplus production framework but sometimes in an age-structured framework, has been conducted in this area to consider the conditions under which a self-enforcing Pareto (economic) optimum can emerge and the opportunity cost of not reaching this optimum, i.e., in comparing the non-cooperative and cooperative equilibriums. The payoffs to players typically depend on the size of a state variable: the relevant resource stock. Brown (2000, pp. 897–898) observes that fishing games create special circumstances that must be considered:

> The existence of stock externalities casts the problem into the context of "dynamic games" in general, and not the special case of repeated games in particular. Fishing is not an infinitely repeated game because payoffs are state variable dependent. P. Dutta (1995) has demonstrated that the intuition developed from infinitely repeated games does not necessarily carry over to the more general category of dynamic games.

Research in this area began with important papers by Munro (1979) and Levhari and Mirman (1980). Munro (1979) was concerned with bargaining solutions in cooperative games. Munro combined the standard bioeconomic model of a fishery with cooperative game theory to show that if cooperative management is unconstrained, so that allowances are made for time-variant harvest shares and transfer payments, then optimal joint harvest requires the player with a lower discount rate to buy out the player with a higher discount rate entirely at the beginning of the program and manage the resource as a sole owner. Levhari and Mirman (1980) applied bioeconomic models to a two-state cooperative game and evaluated the Cournot-Nash equilibrium in which the policy function is linear in the population for non-cooperative, cooperative, and Stackelberg games and the role of side payments in reaching a cooperative agreement in steady-state equilibrium and in which each country has the same discount rate. Brown (2000, p. 897) observes:

> Since open access is just the non-cooperative game with infinitely many players, the cooperative steady state solution with two players at the other end of the spectrum is evident. Cooperation results in a larger equilibrium resource capital stock when there is a common discount rate. When there is a leading country, it exploits its power with greater short run harvest and a lower steady state population.

Fischer and Mirman (1992, 1996), also comparing Nash equilibria and global optima, extended the analysis to interacting species. Vislie (1987) extended Munro's (1979) cooperative game to examine a self-enforcing sharing agreement without strictly binding contracts. Clark (1980) considered a limited access fishery as an N-person, nonzero-sum differential game.

Stackelberg games are non-cooperative sequential move games, where the Stackelberg leader takes into account its ability to manipulate the other agent's decision. The Stackelberg follower follows the Nash non-cooperative strategy. The Stackelberg game is applied when one country has a relatively large fishing industry, and therefore the power to act as a leader, or when stocks migrate, and one country can harvest before another country (Kronbak 2005). Naito and Polasky (1997) apply this approach.

Threats can contribute to the stability of cooperative fishing games (Kronbak 2005). An efficient cooperative strategy can be supported as an equilibrium, by threat of credible punishment, provided the discount rate is low enough. If anyone deviates from a cooperative strategy, the game reverts to the Cournot-Nash one-shot non-cooperative solution. For a low enough discount rate, the short-term gain from defection is offset by the long-term foregone gains from cooperation. Kaitala (1985) examined credible threats for each player in the game, and Kaitala and Phjola (1988) introduced trigger strategies where deviation triggers a switch to play another predefined strategy and examined non-binding cooperative management. Laukkanen (2003) introduced stock uncertainty into Hannesson's (1995a) model with cooperative harvesting as a self-enforcing equilibrium supported by the threat of harvesting non-cooperatively over an infinite time horizon if defections are detected. Hannesson (1995b) considered how cooperative solutions to games of sharing fish resources can be supported by threat strategies. Schultz (1997) and Barrett (2003) discuss trade sanctions.

Munro (1979) began the consideration of a full cooperative solution and Clark (1980) and Levhari and Mirman (1980) considered a non-cooperative solution. Kronbak (2005) observes that the in-between literature addresses the formation of coalitions, where a group of players come together and form a coalition inside which they cooperate and play non-cooperatively against the players outside the coalition. This approach is applied mainly for determining the bargaining power of the players exploiting the resource (Duarte et al. 2000; Arnason et al. 2000; Lindroos and Kaitala 2000). The most recent literature, summarized by Kronbak (2005), discusses how to share the benefits among agents agreeing on joint action and is referred to as characteristic function games (c-games). These games assume that players have already agreed to cooperate and that it is a transferable utility game, and addresses how the agents distribute the benefits from cooperation. The focus is not on side payments but on the distribution of benefits. Kaitala and Lindroos (1998) introduced the theoretical framework, ignoring externalities, and concentrated on benefit sharing rules with exogenous coalition formation. Pintassilgo

(2003) continued this framework and evaluated the stabilities of the grand coalition in the presence of externalities and included endogenous coalition formation.

McKelvey (1997) introduced game theory into a sequential interception fishery where the underlying stock uncertainty is included in the model with a stochastic payoff function. Hannesson (1997) considered fishing as a supergame to analyze the importance of the number of agents exploiting a fish stock for obtaining the cooperative solution. This approach has standard information and is repeated an infinite number of times, has a closed loop, and therefore represents a situation in which a group of agents face exactly the same situation infinitely often and have complete information about each other's past behavior (Kronbak 2005).

Side payments can facilitate cooperative solutions. Munro (1979) first raised the issue. Fishery managers in Olaussen (2007) interact not by harvesting the same stock of fish, but through side payments to a third harvesting agent with stochastic survival of recruits.

Externalities and game theory, although neglected in the early literature, have since received attention. Kaitala and Lindroos (1998) established a cooperative game in characteristic function framework and determined one-point cooperative solution concepts, but their model did not incorporate externalities. Sumaila (1999) summarized research in this area at that time. Pintassilgo (2003) shows that the grand coalition is only stand-alone stable if no player is interested in leaving the cooperative agreement to adopt free-rider behavior, but do not evaluate benefits sharing inside the grand coalition. Eckmans and Finus (2004) recognize the problems with grand coalitions when externalities are present, and propose a sharing scheme for the distribution of the gains from cooperating when a solution belonging to this scheme generates the set of stable coalitions. Weikard (2005) suggests a sharing rule distributing the coalition payoff proportional to the outside-option payoff. Kronbak and Lindroos (2007) discuss the difficulty of coalition payoffs division among members in a characteristic function approach, developing a new sharing rule accounting for the stability of cooperation when externalities are present and players are heterogeneous. Moreover, Kronbak and Lindroos (2007) observe that the stability of cooperation and coalition games is affected by the way that benefits within cooperation are shared among players and that when externalities are present, that additional research is required in this area, that in fisheries coalition games the link between cooperative and non-cooperative games has received insufficient attention due to externalities not receiving attention in cooperative games. Recent research on coalitions includes Lindroos (2004, 2007), Lindroos et al. (2007), and Pintassilgo and Lindroos (2007).

Allocation of shares among the parties, especially developing nations (such as coastal states in international tuna fisheries), is critical for sustaining cooperative multilateral conservation and management and requires additional evaluation. Considerable attention has been given to sharing rules by which the economic surplus from cooperation among nations, as opposed to non-cooperation, is allocated among participating parties, as discussed above. Many models have considered two-agent games, and some authors have considered explicitly the importance of the number of agents for obtaining a cooperative solution.

Fruitful areas of research lie in empirical extensions to highly migratory species, to the area of property rights and incentives, the structure of self-enforcing treaties and agreements, repeated games, enforcement and compliance, multiple agents and the impact on the depth versus depth of cooperation, cost heterogeneity among states, the role of technical change and climate in such self-enforcing agreements (the latter is considered in on-going work by Robert McKelvey and Kathleen Miller), consideration of the rich institutional detail inherent in Regional Fishery Management Organizations, and more sophisticated and realistic population dynamics in bioeconomic applications as discussed above. Benefit sharing and the partition function game approach are important areas of current research. Important applications have been applied to whales (Amundsen et al. 1995). The importance of incentives and rights-based management are two of the most important areas of future research, as discussed in various forms by (among others) Munro (1979), Kaitala and Munro (1997), Barrett (2003), Bjørndal and Munro (2003), and various papers in Allen et al. (2006). Bjørndal and Munro have written extensively in a series of papers about the Law of the Sea, the United Nations Straddling Stock Agreement, and economics.

Another fruitful area of research is the conservation of endangered and threatened species in a transboundary context. One strand of existing literature focuses on the great whales through bioeconomic modeling (Conrad 1989; Bjørndal, and [Au3] Conrad 1995; Amunbdsen et al. 1995; Allen and Keay 2001). Nonetheless, research in this area is in its infancy when taken in the broader perspective of conservation and a more disaggregated approach, and can include the role of rights, incentives, self-enforcing international agreements, mitigation and conservation investments, at-sea conservation measures, optimal regulatory instruments, and other such issues (Dutton and Squires 2008, in preparation; Gjertsen 2007a; Segerson 2007; Heberer and Stohs 2007). Segerson (2007) considers alternative policies to find the optimal balance between the goals of protected species bycatch mitigation and maintaining fishing opportunities, while Heberer and Stohs (2007) considered the choice of cleanest gear (least incidental take rate), and hence treats the regulatory policy as exogenous rather than as a choice variable. Some of the key issues include the cost-effectiveness of alternative conservation measures and interventions in different stages of the life cycle (such as nesting sites, artisanal fisheries, and high-seas fisheries for sea turtles; considerable work is underway in this area by Heidi Gjertsen [Gjertsen 2007b] and Mark Plummer); the relative importance and role of alternative conservation instruments, including technology standards such as gear changes, production standards such as quotas, forms of property rights, conservation in second-best situations such as the simultaneous presence of both transnational and resource externalities. The application of the economics of international environmental agreements to the International Whaling Convention, the Latin American sea turtle treaty, the Indian Ocean-Southeast Asian Memorandum of Understanding, the Agreement on the International Dolphin Conservation Program, and others is another potential area of research. Considerable research has been conducted on the politics and law of the International Whaling Convention (Gillespie 2005), but little formal economics has been conducted with the exception of Clark (1973), Conrad (1989), and Schneider and Pearce (2004).

Yet another fruitful area of research is learning from other international environmental agreements. Conventions and treaties dealing with transboundary pollution, water, and the atmosphere are pervasive (Barrett 2003), but research on ocean issues has only begun to scratch this surface.

The theory of international ocean agreements is still in its infancy. Considerable work in this area has been accomplished (much is reviewed in Barrett 2003; Bjørndal and Munro 2003; Munro et al. 2004; Munro 2006). Contract theory has yet to be fully mined for its insights in this area. Enforcement is a key, because of the principle of state sovereignty, so that these agreements must be self-enforcing (the contracting parties enforce their contract) rather than external enforcement (a third party takes actions as a function of verifiable information, as directed by the contract) (Barrett 2003). How to structure incentives so that parties will agree, changing the game into an induced game with the proper incentives, is a major question. Enforcement and compliance are critical factors, in which trade measures are important and about which little research has been conducted. Standard economic modeling shows that effective monitoring and verifiability are critical to identifying and sanctioning violators. However, analysis has yet to uncover the precise conditions under which cooperation can be supported when information flows in a decentralized manner. Even less understood is how institutions can deal with renegotiation, collusion, and the rescinding of agreements, all of which can interfere with schemes to punish violators. The maintenance of limited entry, dealing with free-riding by non-cooperating members, and critically, rights-based management stronger than limited entry are key areas of concern for future research. New members and IUU fishing are major issues.

32.13 Spatial Management and Marine Reserves

The recognition of the importance of the spatial dimension to management and its role in firm behavior has come relatively late to economics in general and fisheries economics is not an exception. Brown (2000, p. 876) observed:

[T]here is an essential spatial component to living resources. Biota of the same species spatially differentiate themselves and sometimes are then linked together by more or less well defined corridors, as when larvae collect from many separate sources in common pools, then disperse to separate colonies. The peripatetic nature of many renewable resources often makes it prohibitively expensive to bend them suitably into the status of private property.

The economic issues are more realistic representations of fisher behavior, metapopulations, marine protected areas, and spatial rights as a key policy question. Brown (2000, p. 903) observes: “The institutional fabric, including a suitable property rights structure, designed to achieve efficient exploitation of a metapopulation, necessarily differs from the one designed to manage many competitive firms producing for the same market with no technical interdependence.” Brown (2000, p. 909) further observes: “Indisputable economies of scale and non-convexities inherent in the

spatial dimension and behavior of important species invite analysis." Wilen (2004) recognizes the importance of when spatially disaggregated polices are likely to pay off, how different rights mechanisms might be designed, and exactly how altering incentives with direct or indirect instruments affects a spatially exploited bioeconomic system."
[Au4]

The early fisheries work in spatial behavior and management was concerned with the choice of fishing location (Hilborn and Ledbetter 1979) and has subsequently received additional research (Eales and Wilen 1986; Curtis and Hicks 2000; Holland and Sutinen 1999, 2000; Mistiaen and Strand 2000a; Smith 2002; Hutton et al. 2004; Curtis and McConnell 2004). These are all microeconomic production models, so the concerns raised by Wilen (2007) about production models may be germane here. One of the conclusions emerging from this research is that some fleets are comprised of sub-fleets defined by home port, and that some of these respond relatively quickly to profit changes and others which are more sluggish in response; and that highliners seem to be more mobile and opportunistic. Moreover, fishermen behave as economic theory suggests, adjusting high fixed costs and relatively inflexible inputs, such as vessel capital sluggishly, while adjusting other flexible inputs such as vessel days and fishing location much more quickly (Wilen 2004). Research questions in this area include (Wilen 2004, p. 14):

> For short-term participation choices, what are the relevant opportunity costs? What kinds of alternative within-season employment opportunities do skippers, crew, and owner/operators have? How do these affect decisions about whether to fish or not? How different are opportunity costs in fishing, and are these differences responsible for the kinds of heterogeneous behavior that we typically witness?

The spatial dimension has also received attention within the mathematical programming-bioeconomic framework (Holland 2003; Kjærsgaard and Frost 2007), and would benefit from research in the public good framework, thereby capturing non-market benefits such as biodiversity conservation. Important early general papers on metapopulation modeling include Tuck and Possingham (1994) and Brown and Rouhgarden (1997). When modeling spatial impacts, as with all production models, whether disaggregated and static or aggregated and dynamic, and including choice of location, problems exist with simplified production processes that do not capture the richness and complexity of fisher behavior and production and as with all bioeconomic models, simplified population dynamics that do not capture the complexity of populations.

The issue of marine reserves has emerged as one of the policy questions of keen interest, largely arising out of conservation biology. Here the focus extends beyond spatial management and single species to include biodiversity (Hanna 1999). Much of the focus has been on reserves as a form of insurance for the biomass, biodiversity, and ecosystem (Brown 2000; Murray 2007). Arguments for marine reserves often extend beyond the benefits for biodiversity and the ecosystem to increases in resource stocks outside of the reserves that lift catches outside of the reserves. Arguments tend to overlook the bunching up of the fishing capacity outside of the reserves, the length of time and management measures required to deal with the overcapacity that frequently develops, the effects of discounting, the costs of fishing and enforcement and compliance of reserves, density dependence of populations, and biological, environmental, and economic uncertainty. Empirical discussions have yet to properly account for before and after the treatment and with and without the treatment using control areas that control for habitat, environment, species abundance and density, and markets (especially distance from markets). From the perspective of research design (much coming out of the medical and public health literature), there is a glaring absence of research design.

Grafton et al. (2005a) review the recent bioeconomic literature in this area. They observe that bioeconomic models of marine reserves need to consider a number of key processes: the transfer rate and flows between reserves and harvested areas, the effect of reserves on fisher behavior and the influence of environmental stochasticity and shocks on both the reserve and fished populations. Some models assume that total fishing effort is constant and that fishing mortality in the reserve area transfers into the open area. Sanchirico and Wilen (2001, p. 206) observe that most models "consider the problem of carving out a fraction of space in an otherwise homogeneous system in which mixing is perfect, uniform, and generally instantaneous."

Important bioeconomic papers on marine reserves include Holland and Brazee (1996), Hannesson (1998, 2002), Holland (2000, 2002), Sanchirico and Wilen (1999, 2001), Sanchirico (2004, 2005), Smith and Wilen (2003), Sumaila (1998b), Sumaila et al. (2000), Grafton and Kompas (2005), Grafton et al. (2005b), and Murray (2007). Along similar lines, Holland and Schnier (2006) considered ITQs for habitat. Holland and Brazee (1996) found that whether or not increases in spawning stock biomass generate a net increase in the present value of economic benefits depends importantly on the discount rate and the pre-reserve exploitation level, as well as bioeconomic parameters. Hannesson (1998), using a model that is not spatially explicit, showed that a marine reserve in open-access equilibrium is unlikely to improve catches and will create overcapacity. Sanchirico and Wilen (2001) and Smith and Wilen (2003) demonstrate that fishers' spatial behavior is important, and that their models are open access and focus on improving net yields (but not economic welfare since there is open access) when spillover of fish and larvae is sufficient to compensate fishers for lost catches from reserve areas. Sanchirico and Wilen (2001) demonstrate economic results are highly dependent upon the type of interaction between different patches, and which patch is closed, because of complex spatial and inter-temporal effort redistribution. They find that, under open access, most reserve scenarios produce a biological benefit but that there are very few combinations of biological and economic parameters that give rise to both a harvest increase and a biological benefit. In particular, they find that harvest increases are likely only when the designated reserve patch has been severely overexploited in the pre-reserve setting. Sanchirico and Wilen (2001) assume that fishermen respond to profit opportunities by entering and exiting the fishery and by moving over space in response to spatial arbitrage opportunities and find that relative dispersal rates in a patchy system are important in choosing which patchy areas to close. Smith and Wilen (2003) observe that the typical assumptions made by biologists for analytical tractability, such as exogenous and constant effort, consistently bias the predicted impacts in a manner that makes reserves look more favorable than what they might actually be. Smith and Wilen (2003) found that reserves can produce harvest gains in an age-structured model but only when the biomass is severely overexploited and that even when steady state harvests are increased with a spatial closure, the discounted returns are often negative, reflecting slow biological recovery relative to the discount rate. Concerns over production modeling certainly apply here (Wilen 2007).

Uncertainty is important with marine reserves, since a key function is insurance. Murray (2007) observes that none of these models consider uncertainty with the exception of Lauck (1996), Lauck et al. (1998), and Grafton et al. (2005b). Sumaila (1998a) applied a Beverton-Holt bioeconomic simulation model to evaluate a shock in the fishable area outside of a reserve and demonstrated that a reserve can protect discounted rent. Conrad (1999) found that marine reserves can reduce biomass variation when there is a general shock to the system, but that reserves also reduce harvest and rent compared to private property without a reserve. Murray (2007) directly addresses this absence of uncertainty through incorporating parameter uncertainty into a bioeconomic model of marine reserves. Murray (2007) developed a surplus production model with uniform carrying capacity and intrinsic growth rates for the biomass across an open area and reserve area and risk neutrality for fishers. Murray evaluated a Schaefer yield-effort model to show that under parameter uncertainty marine reserves increase the harvest outside of the reserve area and decrease the probability of a resource stock crash in long-term steady-state equilibrium. Additional research would help clarify the uncertainty associated with marine reserves.

Smith and Wilen (2003) raise potential bioeconomic research issues, including whether oceanographic dispersal is the key driver of spatial closure impacts, or whether harvester dispersal may be equally important. Further research is warranted on Smith and Wilen's (2003) observation that whether a particular patch is a source or sink depends on its relative level of exploitation as well as its physical placement in an oceanographic system. These models also need to be extended to more realistically include the endogeneity of regulations, formulated under regulated open access rather than pure open access as argued by Homans and Wilen (1997) in a different context, and state of technology (e.g., VMS or gear restrictions which can be endogenous) as forcefully argued by Homans and Wilen (1997), reflecting further than most fisheries regulation occurs not in pure open access but regulated open access (Homans and Wilen 1997). An open question remains, nonetheless, whether there is sufficient data and analytical techniques to address these questions with any degree of resolution and certainty. The concerns raised about production models by Wilen (2007) are double here because of the oceanographic issues that compound fisheries production modeling.

Some of the critical research for the future requires (Grafton et al. 2005a, p. 173) "[m]odels that explicitly include the spatial behavior of fishers are of particular importance to managers as they emphasize the importance of economic considerations when establishing reserves, and the need to explicitly model the endogeneity of fishing effort in a decision-making framework." Bioeconomic models require allowing for negative shocks and management error or environmental stochasticity (Grafton et al. 2005a). Empirical modeling that incorporates more realistic population modeling will be required to have a substantive impact on policy at the level of the regulator and to be accepted by the practicing population biologists without whose blessings little will be accepted in the policy process. Moreover, as noted by Grafton et al. (2005a), despite many empirical studies on reserves only a few of these investigations include before and after data and spatial variation, well-designed empirical studies are necessary to separate the 'reserve effect' from the 'habitat effect', and to determine the efficacy, or otherwise, of marine reserves. As observed above, this recommendation can be taken further to encourage scientific evaluation that includes before and after treatment (reserves) and, critically, a control group without [Au5] reserves that gives a without and without treatment, all the while controlling for the habitat and environment effect. Equally important are the uncertainties in terms of the 'connectivity' between reserves and no-take areas at the larval, juvenile, and adult stages, and also critical habitat size, renders the problem of determining the size and location of reserves a very difficult task. Moreover, fishing spillovers from reserves very much depend on their design and must consider advection, as well as diffusion processes, and an appreciation of both dispersal distance and the number of population sources. Bioeconomic modeling has yet to fully incorporate density-dependent theory in which yield-per-recruit effects that are lowest at carrying capacity, i.e., unfished populations, that compensation at lower population levels, i.e., fished populations, produces a sustainably harvestable surplus, and lower body growth rates at higher population densities. The effects of stochastic recruitment, where recruitment might be a function of the environment, have not yet been considered in a bioeconomic model. A full economic assessment of the net benefits from reserves would also have to account for the total economic value, including non-market values from biodiversity and ecosystem benefits. The full relationship between marine reserves to restore and maintain biodiversity and ecosystems, raise catches (through the spillover of adults and the export of eggs, larvae, and juveniles as the density of fish populations within reserves increases), and act as insurance and "standard" fisheries management, as discussed for example by Hilborn et al. (2006) and Roberts et al. (2005), also remains unsettled and a potential research topic. Armstrong (2006), in a review paper, states that "much work still remains with regards to the analysis of different management options than solely open and limited access outside marine reserves."

Bycatch and reserves remain an under-researched area (Armstrong 2006). Bonceur et al. (2002), in one of the few papers in this area, apply a two-species, two-area model of marine reserve implementation. Reithe (2006) and Armstrong observed that the ecological interaction also affects the possibility of obtaining a win-win situation when implementing a reserve, and also determines the optimal patch to close. What about two potential reserve areas and closing only one and one area benefits one species and the other area benefits another?

Specific potential research questions in the context of spatial management relate to (Wilen 2004, p. 16)

> management system design with mixed public and private values and mixed consumptive and non-consumptive services. What kind of spatial system might be used to manage both kinds of services? Would it be best to manage a mixed system with a mix of closed areas

> and spatially regulated restricted access policies, or would it be best to move directly to clarifying and allocating a system of restricted property rights? If partial rights systems are developed, what are the implications of different degrees of specificity, transferability, and excludability?

As noted before, the underappreciated element in these schemes is the collective action problem arising with their institutional and managerial organization. Compounding this difficulty is the ability of management institutions to actually implement such fine-tuning at the margin (see Schrank 2007 for the difficulties of such fine-tuning and use of structural models in the context of TACs), and the ability to actually achieve compliance and enforcement with fine spatial scales (horizontally and vertically within the water column) and imperfect monitoring.

32.14 Risk and Uncertainty

Risk and uncertainty are pervasive in fishing industries due to multiple sources, including markets, regulatory institutions, technological change, the resource and ecosystem, environment, climate, oceanography, and other factors. The environment, climate, oceanography, resource stocks, and ecosystem are inherently stochastic, i.e. partly random. Insufficient knowledge about these future states of nature is complicated because even less is known about the social and economic impact of alternative policies, compounded by the long time horizons in climate and ecosystems (Pindyck 2007). Little is known about the current and future costs of a policy; how will fishers respond to alternative policies? Resource and environmental cost and benefit functions tend to be highly nonlinear (or even nonconvex), so that for example, environmental and ecological costs may be very low for low harvest rates but then become extremely high for higher harvest rates. Ecological resiliency may be robust until a threshold or tipping point occurs at which point the impact of a harvest policy becomes extremely severe. The precise shapes of these functions are also unknown. What discount rate should be used to calculate present values? In the broadest sense, policy-makers and scientists never really know what the benefits and costs will be from alternative policies, what discount rate is appropriate, and what the resource stocks and ecosystem will look like in the future (or even the present). Irreversibilities may also arise, such as extinction, permanent changes in species mixes from harvest policies (think of New England groundfish). Very long time horizons may also be involved, so that the effects of discounting might not fully capture the long-term effects on the ecosystem and climate; what is the full impact of the interplay between climate and harvest policies for northern cod? A long time horizon compounds the uncertainty over policy costs, benefits, and discount rates. Uncertainty also arises over the type, extent, timing, and impact of technological change that could ameliorate the economic impacts and/or reduce the policy costs. Weitzman (1974a) considered the implications of uncertainty for optimal choice of policy instruments; this has been studied extensively in environmental economics, and has received some attention in fisheries economics.

Much of the early work in bioeconomics assumed that the growth function for the resource stock is known and deterministic, when in fact the growth function is stochastic and even highly stochastic (Pindyck 2007). The stock dynamics might be better described by a stochastic differential equation. As is well known to population biologists, the actual resource stock cannot be observed, but can only be estimated subject to error (including relying on fishery dependent data). The optimal resource management problem then becomes a problem in either stochastic dynamic programming or stochastic dynamic simulation. How do stochastic fluctuations in resource growth affect the optimal regulated extraction rate (Pindyck 2007)? What is the optimal policy if there is an increase in the volatility of stochastic fluctuations in the resource stock as the stock becomes smaller and the potential for irreversible decline to extinction arises?

Although this is one of the most important topics of research, much remains to be done in fisheries economics on the choice of optimal policy instrument under uncertainty and even on understanding the very nature of the uncertainty confronting industry and policy makers. Important works include those by Reed (1979), Andersen (1982), Andersen and Sutinen (1984), Clark and Kirkwood (1986), Bockstael and Opaluch (1993), Dupont (1993), Grafton (1994), Li (1998), Mistiaen and Strand (2000b), McDonald et al. (2002), Weitzman (2002), Eggert and Tveteras (2004), Eggert and Martinsson (2004), Grafton and Kompas (2005), Saphores (2003), Herrara (2005), Sethi et al. (2005), Singh et al. (2006), Kugarajah et al. (2006), McConnell and Price (2006), Murillas and Chamorro (2006), Nøstbakken (2006), Segerson (2007), Eggert and Lokina (2007). Research topics include further examination of fishers' risk preferences, fishery management under uncertainty, including Bayesian decision analysis, irreversibilities, extinction, and accounting for rare events (e.g., sea turtles poised on the brink of extinction) in policy, closer examination of the tails of distributions, and how these may change over time rather than just central tendencies, risk, and uncertainty in ex-vessel price and ITQ markets, uncertainty of regulations, optimal policy instruments under uncertainty, causes, and likelihood of severe or catastrophic outcomes, nonlinear benefit and cost functions, and credible bioeconomic models explicitly dealing with uncertainty, perhaps through Bayesian approaches as practiced by population biologists. Many of the issues raised by Pindyck (2007) can be adapted to potential research in fisheries economics.

32.15 Bycatch and Multispecies Issues

Bycatch is simply fish or other species caught as part of a joint production process, but fish that are an undesirable output. Incidental takes can also occur for sea turtles, dolphins, other cetaceans such as whales, sea birds, and other species. In economics, some progress has been made in bioeconomic framework (Boyce 1996; Herrera 2004; Enriquez-Andrade and Vaca-Rodriguez 2004). Herrera (2004) and Jensen and Vestergaard (2002c) consider the problem of strategic interactions between catch-discarding fishermen and a regulator, a moral hazard problem. Directional distance functions are a promising approach to evaluate the microeconomic joint production process with bycatch (Färe et al. 2006), since they allow for both weak and strong disposability of target catches when bycatch is reduced, along with extensions to include the environment and its effects and the potential for underutilized capital (Kjærsgaard et al. 2007). Another promising approach, by Abbot and Wilen (2007) builds on game theory and develops a firm-level positive analysis in a second-best framework to analyze the intra-seasonal game played between fishermen and regulators even when complete and perfect information is available on all sides. Segerson (2007) developed an alternative approach within a static environment applying models originally developed in the environmental economics literature for undesirable outputs such as pollution while explicitly incorporating uncertainty. More modeling work remains to be done in both areas. Policy work remains in the area of property and use rights and economic incentives.

32.16 Buybacks

Buybacks of vessels, gear, or rights are widely used throughout the world although buybacks are largely, but not universally deplored, by economists. Considerable recent work has been done on evaluating buybacks as a policy instrument and their design by Holland et al. (1999), Groves and Squires (2007), Hannesson (2007e), and Curtis and Squires (2007), but little formal economics research has been conducted with the exception of Sun (1998), Campbell (1989), Weninger and McConnell (2000), Walden et al. (2003), Kitts et al. (2001), Guyader et al. (2004), and Clark et al. (2005, 2007). Fruitful and obvious topics of research include the design of auctions and accounting for information asymmetries including moral hazard and adverse selection, and evaluating the impact of incentives (Curtis and Squires 2007). Other than the important work of Weninger and McConnell (2000) and Clark et al. (2005, 2007), little formal modeling of investment in this context has occurred. Investment modeling would be best served with a disaggregated output vector more closely corresponding to the actual decisions made by fishers. Another important area is the role and design of buybacks for conservation purposes, especially in developing countries, such as the vaquita or for sea turtles, in which willingness to pay for existence values from developed countries is expressed. Since buybacks can be viewed as a form of contract, buybacks should provide a fruitful area of research for contract theory.

32.17 Aquaculture

Increasingly, cultured fish and other seafood comprise much of the fish that is consumed, and cultured fish and other seafood can be expected to comprise ever-increasing amounts. Only a few salient issues will be touched upon on this under-researched but increasingly important topic. Rising final demand for cultured seafood raises the derived demand for a critical input in the production process, fish meal, and other fish feed often derived from small pelagic species such as anchovies and sardines. These fish in turn are often forage fish for other species in the food web, so that growing demand for small pelagics not only raises the issue of overfishing but also impacts upon the ecosystem; finding the right balance in an era of ecosystems management presents an important research topic. Just what are the economic and strictly ecological values of alternative pelagic species in the ecosystem? For example, the value of menhaden in Chesapeake Bay is under consideration, with menhaden serving as a reduction species for fish meal, for a source of Omega-3 for direct human consumption, as primary feeders and forage fish in the ecosystem, and other ecological and human purposes. The interaction and effects of cultured species, such as some species of salmon, with wild species presents another research topic, as for example, interbreeding. Wastes and diseases from cultured fish can also impact other species of fish and the surrounding ecosystem. Conflicting uses of the land and offshore areas for culture and other purposes is another concern.

32.18 Experimental Economics

Experimental economics entails laboratory experiments, i.e., formal scientific experiments with carefully constructed hypotheses and formal controls to evaluate the effects of various treatments. In contrast to most economics and population dynamics, this approach closely follows laboratory approaches routinely used by many scientific disciplines. Experimental economics can be used to evaluate many areas of economics, but is separately distinguished due to its uniqueness. This approach has been widely used in public and behavioral economics for many years, but is only now starting to be applied in fisheries economics to areas of auctions and their design, property rights, and incentives, largely by Chris Anderson of the University of Rhode Island (Anderson and Sutinen 2005, 2006; Anderson and Holland 2006). This promising approach can provide new insights into auctions, property rights, and behavioral economics applied to fisheries.

32.19 Behavioral Economics

This important area of research in finance and theoretical economics has yet to be applied to fisheries economics and will only be briefly touched upon. In essence, behavioral economics widens the behavioral hypotheses of economic agents – consumers and producers – from strict self-interested rationality of the individual economic agent. Behavioral Economics is the combination of psychology and economics that investigates what happens in markets in which some of the agents display human limitations and complications. Humans deviate from the standard economic model in several ways, including (Mullainathan and Thaler 2000):

(1) bounded rationality, which reflects the limited cognitive abilities that constrain human problem solving; (2) bounded willpower, which captures the fact that people sometimes make choices that are not in their long-term interest; and (3) bounded self-interest, which incorporates the comforting fact that humans are often willing to sacrifice their own interests to help others.

32.20 Invasive Species

Invasive species represent an increasingly important policy issue facing nations and hence is growing in research importance. The spread of exotic species into ecosystems and threats to biodiversity and sustainable resource use represent both an ecological and economic problem. Management of invasive species entails the expenditure of limited resources, which must be carried out in the most effective manner. Little will be mentioned here of this topic, other than to note its growing importance and several key extant research papers. A key question, as with pollution, is the optimal level of invasive species eradication, prevention, or ongoing management, all of which depend on the current level of invasion and the nature of the recipient ecosystem, which is essentially a cost–benefit question. Other fundamental questions include the potential importance of linking the dynamics of the invasive species with the behaviors of individuals and institutions. How do individual behaviors and decisions lead to invasion? How are externalities incorporated into models, since invasive species automatically entail social costs not adequately considered in the decisions facing individuals?

32.21 Concluding Remarks

The key ideas introduced by fisheries economics that have resonated with policy-makers and other disciplines have been the importance of property rights and incentives for the conservation and management of fisheries, ecosystems, and biodiversity. These ideas have permeated the fields of population dynamics, ecology, and conservation biology, and are routinely considered by policy makers. The importance of incentives is just becoming clear in conservation, especially of transnational global public and common resources.

The main thrust of fisheries economics is the development of normative economically optimal harvest strategies, but the results have largely failed to resonate with policy-makers, industry, and other disciplines. This is in part because of the discordance in how population dynamics and uncertainty are approached and modeled compared to the far more sophisticated population biology used in management, and in part because questions centered on prediction and distribution rather than normative are relevant for actual management. In this regard, contemporary and comprehensive population dynamics and stochastic dynamic simulations rather than normative economic optimization are critical for policy relevance. As observed by Deacon et al. (1998, p. 392), "[s]tylized optimization-based models probably have already yielded their most important insights," and (Deacon et al. 1998, p. 392), "[i]f we are interested in being useful beyond offering simple generalities, however, then it is time to begin incorporating more of the realism that already exists in the biological literature into our models." Nonetheless, there is room for the on-going incorporation of environmental services and biodviersity into a more comprehensive normative bioeconomic model. In any case, the main focus of formal fisheries economics research has by choice largely confined itself to an internal discussion of a focused topic. The seminal developments in the field were largely introduced outside of the economics profession (Warming 1911; Gordon 1954), or by economists outside of academia (Christy 1973, 1982; Sinclair 1961), with the singular exception of Scott (1955a, b).

Important ideas for future research include: (1) to better understand the workings of new forms of use and property rights as they evolve for not only fisheries management but also conservation of biodiversity and the ecosystem (especially territorial rights such as TURFs, fishing cooperatives, and the global ocean commons) and climate responses; (2) technical change and more generally, productivity growth (fishing power); (3) valuation and modeling of ecosystems and ecosystem approaches to management using the concept of natural capital and its flow of services; (4) conservation of protected species and habitat and biodiversity in general, as forms of pure and impure public goods; (5) analysis of Pareto-improving policies in a second-best world, i.e., less emphasis on a normative economic optimum under ideal conditions and greater emphasis on policies that improve economic welfare broadly defined under conditions that are less than ideal; (6) bioeconomic models closely aligned to current population dynamics and that rely less on analytical solutions and that allow for technical change (which current population dynamics allows); (7) broadening bioeconomic models to incorporate ecosystem management (as well as more realistic population dynamics and consideration of uncertainty); (8) international treaties, transboundary resource stocks, transnational fisheries, and international trade; (9) better understanding fishing industries as industries and the regulatory process as regulation of an industry under asymmetric and incomplete information; (10) better understanding the risk and uncertainty that pervades economic models and conservation and management of fisheries, biodiversity, and ecosystems; (11) aquaculture; and (12) developing country fisheries, including various scales of coastal and artisanal fisheries.

Let me finish with a few personal observations. As fisheries, especially in developed countries, evolve from purely commercial interests to concerns over the public good components – as fisheries in these countries are increasingly viewed as an environmental, ecological, and biodiversity issue rather than simply an extractive industry – the locus of research in these countries will follow suit. Environmental and public economics, ecology, and conservation biology will increasingly serve as the defining intellectual framework in what is known as ecosystems management and conservation. Traditional fisheries economics, with its focus on normative optimal harvesting strategies – pure extraction – will remain important to academic fisheries economics, but continue to languish inside management agencies where the concern is largely over predictive and distributive rather than normative concerns. The most interesting and pressing research questions will shift to those now voiced by society about how to best mix commercial fisheries and private goods with environmental, ecological, and public good concerns over biodiversity, healthy ecosystems and their services, and sustainable resource use.

Fisheries in developed countries increasingly focus on fresh, high-value fish caught by lines and traps and aimed at restaurants and “high-end” markets. Bottom trawls and ecologically harmful fishing practices are phasing out with some notable exceptions such as the Alaskan pollock fishery. Mass consumption is increasingly filled by international trade and developing country fisheries and aquaculture. In short, as emphasis shifts to environmental sustainable fishing, healthy ecosystem and their services, and biodiversity conservation, former environmental issues are exported out of sight and out of mind. The issues do not go away; they simply reside elsewhere, which raises the important research topic of sustainable fisheries and aquaculture in developing countries along with the link of international trade as well as the growing domestic consumption within these developing countries.

Concern continues to mount over the global public good of the atmosphere, and a similar concern can be expected to grow over the global ocean commons, raising the issue of transboundary fisheries and biodiversity conservation with an environmental and public good twist, such as whales, sea turtles, coral reefs, and the like. Game theory, contract theory, and public and environmental economics will become increasingly important as intellectual frameworks. Technical change is one of the most important contributors to the growth in fishing capacity, biodiversity loss, and environmental degradation, and increasing research attention in this area is critical, including appropriate (largely second-best) policy responses. The presence of technical change obviates the notion of a steady-state equilibrium, and making normative renewable resource models relevant will require grappling with technical change and the continuing disequilibrium. Technical change has been studied extensively for other industries and this body of work suggests many important and relevant research questions. In addition, there is no substitution possible between the resource stock, man-made inputs and technical change; a lower resource stock through the impact of ongoing technical progress simply leaves less catch at some point, and theoretical and empirical research opportunities into this process are many. The effects of technical change and understanding what drives technology and its diffusion are important. Risk and uncertainty will remain as complex and critical issues of concern, especially as economists confront the limits of what are admittedly over-aggregated and highly abstract models concerned with shifting oceanography and ecosystems in the complex dynamic process of the oceans. Consideration of the tails of distributions – rare events or the “Black Swan” – is critical for conservation issues. Climate change will become an increasingly critical issue for oceans and fisheries. Fisheries and development economists have only begun to scratch the surface of the resource-based development of millions of artisanal and commercial fisheries in developing countries, and the intellectual foundation for this worthy project lies in the nexus of resource, environmental, and development economics. Much can also be learned from agriculture and terrestrial conservation economics.

Increasing interest is shown over spatial processes and territorial rights as a means to internalize or address the spatial externalities and processes and metapopulations present in the oceans. Considerable normative modeling efforts are given to this issue, with ecology and oceanography as important intellectual components. The degree of resolution and certainty of the results and the ability to manage off imperfect aggregate and largely normative models remain open questions, and care should be given not to oversell what can realistically be achieved. Much of value will undoubtedly be learned of a qualitative and general nature that can shed light on optimal policy. Concomitant with this normative modeling will be greater thought given to spatial elements in conservation and management and the nature of zoning and territorial property rights. Spatial economics, landscape analysis, and GIS provide good sources of research ideas and topics.

In sum, the central and continuing theme of economics that the proper formation and functioning of institutions – including property rights, evaluation of trade-offs and opportunity costs, and economic incentives will continue as the most important and enduring message from economics. Fisheries economics has insufficiently taken advantage of other fields of applied and theoretical economics for methods and research topics to understand fisheries as industries within either a positive or normative framework. Most importantly, the focus of economics' recurring themes will increasingly shift from the classic overfishing problem to the three great challenges facing humanity in addressing global oceanic environmental problems: sustainability of ecosystems and their services, loss of biodiversity, and the oceanic interaction with the atmosphere through climate. That is, rather than simply addressing the classic overfishing and resource stock externality issue identified by Warming (1911), Gordon (1954), and Scott (1955a, b), fisheries economics will rise to the challenge of addressing multiple externalities and a broader concept of sustainable resource use, often in a second-best rather than first-best context: the timeless resource stock externality, the transnational externality for transboundary and straddling stocks and global public goods, and those externalities arising from the public good issues of biodiversity conservation and sustainability of ecosystems and their services. The benefits of these three great challenges are largely non-market and non-use with important future values, so that their research challenge requires fisheries economics to stretch their standard dynamic models and reliance on markets and reach beyond the well-established confines of fisheries economics.

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