The Economics of Production in Marine Fisheries

Dale Squires and John Walden

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D. Squires (✉)
NMFS, Southwest Fisheries Science Center, La Jolla, CA, USA
e-mail: dale.squires@noaa.gov

J. Walden
NMFS, Northeast Fisheries Science Center, Woods Hole, MA, USA
e-mail: john.walden@noaa.gov

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S. C. Ray et al. (eds.), *Handbook of Production Economics*,
https://doi.org/10.1007/978-981-10-3450-3_34-1

Abstract

Production economics is important to the economic analysis and public regulation of fishing industries in order to address the market failure associated with a common renewable resource stock. Application of production economics arose out of bioeconomic analysis of the aggregate fishery production framework. Production economics gained in importance as it, along with econometrics and mathematical programming, developed as fields. Coupled with an industrial organization orientation and public regulation focus, production economics contributed to analyses of fishing industries, and addressed the underlying market failure. Compared to bioeconomics, this reorientation shifted the focus to shorter time periods and to the individual firm – usually the vessel – and to multiproduct, multi-input production. Production economics now contributes to further development of the bioeconomic model, and addresses additional sources of market failure in fishing industries arising from pure and impure public goods associated with new technology and biodiversity, as well as ecosystem services impacted by fisheries. The chapter reviews the historical developments of production economics applied to fisheries, and concludes with potential future directions forward.

Keywords

Economics · Production · Marine fisheries · Common resources · Industrial organization · Productivity · Efficiency

Introduction

Beginning in the 1950s, the problem of the “commons,” particularly in relation to fish resources, started to generate interest among economists. Economists sought to answer questions centered on resource depletion, dissipation of economic rents due to absent or ill-structured property rights, the optimal number of fishing vessels, and appropriate harvest rates. Subsequent empirical work showed the accumulation of physical capital starting to occur in fisheries [21, 186]. These studies were among the first that used data collected from a specific fishery to show a result that policymakers could use to restrict capital in a fishery. The introduction of economic tools and resulting policy advice was timely because the biological models used by regulators at the time were insufficient to provide coherent policy advice in the presence of increasing capital, and perhaps more importantly, technological change. Into this void, economic models and thought, which had slowly been developing, were well positioned to provide policy advice to fishery managers. At the heart of this guidance were models grounded in modern production economics.

The introduction of production economics into questions surrounding fishery management began with seminal work by Gordon [90], Scott [197], and Smith [202]. Gerhardsen [88] also wrote another very early economics paper. These papers established the theoretical basis for rent dissipation and overcapitalization under open access and how the rent-maximizing fishery would entail lower levels of capitalization (or effort). They assumed a fleet of homogeneous fishing vessels with the same underlying production technology and cost functions, and a fish stock assumed to be under a stationary condition. The surplus production framework and aggregate production function from the biologist Schaefer [193] were typically adopted. The total number of vessels that could fish was usually viewed as the control variable in the system, and the objective was to understand the relationship between the number of vessels, harvest levels, and remaining stock size, within an objective of maximizing economic rent. Overall, these aggregate models provided policymakers with advice that could be used to limit fishing effort within the constraints of the productivity of the underlying fish stocks. They also improved the biological models of the time, which were void of economic thought.

The aggregate production framework was limiting, and by the late 1960s and early 1970s researchers started to specify models based on modern production theory focused on individual vessels as firms. In one of the first studies, Comitini and Huang [46] estimated production functions for a panel of 32 fishing vessels. This was followed by Carlson [39, 40], who used cross-sectional data from the New England trawl fleet along with the tropical tuna purse seine fleet to estimate generalized production functions for the two fleets. To move away from effort as an aggregate input, which had been the dominant approach in the aggregate production framework, Huang and Lee [113] and Anderson [9, 10] developed models that recognized fishery production as a two-stage process, with an intermediate output (effort) being used as an input for the final output (landings). This period firmly established modern production theory as a tool that could be used to model the fishing production process and provide relevant policy advice for managers.

Hannesson [99], the first to introduce modern concepts of production economics and empirical analysis, applied separability to fishing effort specified as a composite input. He also introduced (disembodied, exogenous) technological change, (deterministic) frontier functions, technical inefficiency, and functional forms beyond the Cobb-Douglas, notably the homothetic frontier of Zellner and Revankar [261] and the translog. Influential work by Squires [205–211], Kirkley [122], and Kirkley and Strand [126] introduced dual-based methods and other flexible functional forms to examine the underlying multiproduct costs and production technology (especially input and output substitution possibilities) and the nature of joint production for multioutput, multi-input commercial fishing vessels and public regulation of groundfish trawlers in New England. The dual-based approached readily allowed disaggregation of aggregate output and input (i.e., effort) into individual products and inputs, specifying exogenous prices as regressors, and testing for various types of separability and joint production. Bjørndal [24], Dupont [56, 57], and Bjørndal and Gordon [26] further developed the dual approach in fisheries, including the impact of restricted inputs, while examining practical problems in the British Columbia salmon, Scandinavian herring, and other fisheries and further introducing contemporary empirical analysis.

In short, the empirical models developed during the 1980s and early 1990s ushered into fisheries the era of modern production economics. These models shifted analysis beyond the popular aggregate bioeconomic models of the time to empirical firm-level analysis applying rigorous microeconometric techniques to cross-sectional and panel data on individual fishing vessels, flexible functional forms, duality, concepts of multiproduct costs and production, homotheticity, separability, and aggregation, joint production, technological change, and more advanced econometric estimation techniques that were emerging in production economics and econometrics. These empirical analyses explicitly recognized the multiple-output, multiple-input joint production nature of the fishing firm's production process, which had not been fully explored at that time, although clearly recognized by Comitini and Huang [46, 47], Carlson [39, 40], Huang and Lee [113], and many of the other early production economists.

Applying production concepts to multiproduct revenue- and profit-maximizing firms with endogenous products in the face of public regulation addressing common resource market failure led to a number of extensions of production economics to topics relevant to fishing industries. Squires [206, 207, 209], Segerson and Squires [198, 199], Kirkley and Squires [124], Färe et al. [70], and Lindebo and Vestergaard [145] extended the economics of capacity and capacity utilization to maximization of short-run profits or revenues with endogenous multiple outputs and accounting for a second capital stock (in addition to physical capital), the natural capital stock. Squires [206, 207, 209, 211] and Squires and Kirkley [216] extended the short- and long-run multiproduct cost structure from firms minimizing the costs of exogenous or predetermined single and multiple products to revenue- and profit-maximizing firms with multiple endogenous products. Segerson and Squires [198] further develop the ray measure of multiproduct returns to scale plus two original alternatives. Herrick and Squires [105] and Squires [210, 212] extended total factor productivity and index numbers to account for multiple species of the natural capital stock using consistency of multistage aggregation and superlative index numbers. Segerson and Squires [199], Squires [213, 215], Squires and Kirkley [216, 218], Dupont and Gordon [58], Asche et al. [16], Ekerhovd [66], and Hansen and Jensen [103] extended virtual price [161] and virtual quantity theory [160] to rations and quotas and the related shadow price approach to individual nontransferable and transferable quotas on catch and effort. Asche [13] developed a dynamic revenue function with adjustment costs. Dupont [57] developed the relationship between Diewert's [54] elasticity of intensity and the conventional price elasticity of input demand. Squires [215] extended the elasticity of intensity to allow for adding or removing quantity controls (using virtual prices and quantities).

By the early 2000s, input and output distance functions were applied to commercial fishing fleets at the vessel level [76, 124, 125, 247, 257]. Distance functions were used in response to concerns about capacity and excess capacity in commercial fisheries [60, 130, 131, 172, 250]. (See Squires and Segerson [220] for a review of capacity and capacity utilization including fisheries.) Kirkley and Squires [124] and Kirkley et al. [127] first applied data envelopment analysis (DEA) with output distance functions and the stochastic production frontier (SPF) to analyze technical efficiency and fishing capacity. Distance functions have subsequently been used to answer questions about discards, product transformation possibilities, and to value fishing vessel capital [73, 75, 173, 175, 194]. Distance functions are far less restrictive than a production function based upon a specific functional form.

The balance of this chapter discusses vessel-level production models and a deeper discussion of capital, labor, management, or skipper skill, and effort as inputs in the vessel production function. Next, dual-based methods using revenue, profit, and cost functions are reviewed. Distance function and directional distance function models follow. We then discuss multiperiod production models and dynamics, productivity measurement, and technical change, along with examples of economic growth models applied to fisheries. Using the theory of production concepts developed in the chapter, we conclude with a discussion of the aggregate production framework typically found in bioeconomic models.

Vessel-Level Production

Comitini and Huang [46], in one of the first examples of vessel-level production, specified and estimated Cobb-Douglas and constant elasticity of substitution (CES) production functions. Results showed differences in vessel productivity, which they attributed to the managerial ability of the captains (“skipper” effect). Carlson [39] specified production functions for New England trawl and the tropical tuna purse seine vessels. The study was the first to extend capital input beyond a single characteristic, such as vessel horsepower. Instead, capital input was defined as gross tons, horsepower, hull construction (i.e., steel vs. wood), and vessel age. Labor was still defined as crew size, and the study recognized the “skipper” effect on vessel productivity. Productivity of the fishing grounds was accounted for by home port dummy variables. Finally, although data were not available to test for technological change, it was the first to recognize technological change as a component of the production function. Other early empirical production function studies included Comitini and Huang [47], MacSween [148], Liao [144], Buchanan [32], Comitini [45], Hussen and Sutinen [116], Taylor and Prochaska [234], Strand et al. [232], Holt [110], Hannesson [99], Kirkley [122], Staniford [230], Greenberg and Herrmann [95], Agnello and Anderson [4], Bjørndal [25], and Campbell and Lindner [36].

These early studies, consistent with the applied economics of the time, did not consider the potential endogeneity of inputs (or simply appealed to the maximizing of expected profit discussed by Zellner et al. [262]), areas fished, and ports, or fully employ panel data techniques (one-, two, or three-way fixed and random effects, mixed effects). They largely preceded flexible functional forms for the production function, generalized approaches to addressing error terms for heteroscedasticity and serial correlation, or quasi-experimental methods (such as difference in differences) for causal inference on policy or other issues.

Other influential production function studies include Grafton et al. [94], who evaluated the impact of individual transferable quotas in the earliest “modern” microeconomics approach of evaluating natural experiments. Wolff et al. [260] utilized three-way fixed effects to distinguish vessel and skipper effects. Horrace and Schnier [112] specified fixed effects for area, and Natividad [159] utilized difference in differences to evaluate the causal effect of individual transferable quotas (ITQs) on catch and productivity of the Peruvian anchovy fishery. Zhang and Smith [263] specify a two-stage estimation method to address the latent stock problem with errors in the production function and stock dynamics. Fousekis and Kolonaris [82] and Weninger and Strand [258] estimated the first multiproduct production (distance and ray) functions.

Capital

Nøstbakken et al. [165] lists natural, physical, human, and immaterial capital as distinct categories of capital in a fisheries framework. Natural capital refers to the fish biomass S_t. Except in the case of a sole owner fishery, natural capital (S_t) is never under the control of an individual fishing vessel. Human capital refers to the labor input, and has been studied by some in the context of skipper skill as discussed below. Immaterial capital refers to assets such as fishing rights. In this section, we will focus on physical capital K_t, which is the vessel and equipment that is needed to conduct fishing operations.

Aggregate industry K_t in a fishery is the sum of all the capital on individual vessels participating in the fishery. The perpetual inventory method provides a more comprehensive measure of K_t than simply vessel counts by inventorying entering and exiting vessels, differences in productivity between newer and older vessels, and depreciation [150]. This method, however, requires detailed data collection that is often not collected regularly. The value of capital (K_t) can also be estimated through the use of insurance surveys, surveys of secondhand prices, book values, or prices of newly constructed vessels [183]. Kirkley and Squires [123] specified a hedonic model to estimate vessel value for a fleet of vessels operating off the eastern US coast. Färe et al. [75] estimated capital values for a group of fishing vessels in the eastern USA based on secondhand sales advertisements from commercial vessel brokers and an input distance function. Mean values for the capital inputs based on the distance function model were used to construct a Lowe capital quantity index.

The vessel stock K_t needs to be turned into a flow of capital services. The dual approach is through the user cost of capital or the Christenson-Jorgenson capital services price [42]. Squires [206–208, 210–212], in the first estimates, assumed an opportunity cost of K_t equal to the rate of return on a BAA rated bond, which is considered a "risky" bond, and an economic depreciation rate of 7%. Fisheries studies typically assume there is no "unanticipated revaluation" of physical capital (capital gains or losses), but could apply to an asset like an ITQ share. Aggregate capital services costs aggregate over individual asset types and ages. Primal measures of capital services are through multiplying K_t by a measure of time, such as days at sea or days fishing.

Labor

The crew (i.e., labor) is typically rewarded using a "lay system" rather than an hourly wage rate. These arrangements have existed for well over 100 years. Crew is compensated with a percentage of the revenue from a fishing trip either before or after trip costs are deducted. There are a wide variety of lay systems in place, and who pays for the trip costs is an important part of each system, as well as the split of revenue. When crew are paid through shared remuneration systems, the sharing within crew members is often not homogeneous, highlighting differences in marginal productivity and payment of labor quasi rents.

Shared remuneration systems vary across the globe [96], including four remuneration systems commonly used in fisheries: (1) fixed remuneration systems, (2) shared remuneration system: proportional to catch or revenues, (3) shared remuneration system: proportional to revenues minus operational costs, and (4) shared remuneration system: proportional to profits. Sometimes fishermen's remuneration includes two or more features of these classifications.

The lay system, similar to crop sharing, is usually explained as a means of sharing risk [231], and is widely used in fisheries worldwide [153]. Vestergaard [244] recognized risk sharing in lay systems, but also characterized these arrangements as a principal-agent issue. This is particularly evident if supervision of workers' effort is unobservable, costly, or ineffective [231]. Vessel owners often do not participate in fishing, but instead hire a captain and crew to fish their vessel for extended periods of time. The share system allows the owner to both share risk and lower their monitoring cost. McConnell and Price [153] suggest that moral hazard and team agency can explain the share system. Moral hazard exists because individual effort is usually unobserved by the vessel owner, which leaves stochastic harvest as the only output of crew effort. Team agency conflicts come about because individual fishing crew independently allocate effort which is both costly and unobservable [153].

The role of the lay system in commercial fisheries, and how it impacts vessel production, has not been as extensively studied as other topics in fisheries production. Early studies include Sutinen [233], Plourde and Smith [182], Craig and Knoeber [48], and Matthiasson [151].

A lay system changes some of the behavioral assumptions which underlie the usual neoclassical production model. Since the share system allows the crew to share in revenue earned on a fishing trip, they may be earning more than their opportunity cost, meaning they are earning an economic surplus (i.e., economic rent) from their participation in the fishery [96]. Revenue maximization may then be a better assumption than profit maximizing, or cost-minimizing behavior when modeling fishing vessel behavior [13]. Moreover, incentives for investment in an individual transferable quota, or ITQ system, may become distorted, so that the presence of a share system could lead to either overinvestment or underinvestment in vessels depending on the share which goes to the boat owner [100].

McConnell and Price [153] addressed whether the lay system distorts empirical fishery production model results. They cautioned that the presence of a share system may undermine econometric results (e.g., create biased and inconsistent parameter estimates) from random utility models or dual-based production models, in which input demand for labor cannot be derived. This model limitation is overcome when the analysis is an economic one that uses the opportunity cost of labor as a shadow wage rate and shadow prices for other inputs when appropriate and capital services prices rather than a private or financial analysis that uses observed prices [238–240].

Management or Skipper Skill

The firm's management in fishing industries is known as the skipper effect or the "good captain hypothesis." The firm's management can also be viewed as part of the larger issue of unobserved heterogeneity between firms and unobserved inputs in general, which extends beyond the individual firm's management to include multiple unobserved factors that influence production [157]. When management is specified as a residual, it includes the effects of factors that do not depend on management, but rather on the firm's particular environmental conditions.

Vessel management and this residual have been addressed in several different ways. Authors looked for skipper effects by examining the size of the residual variance remaining in the analysis of vessels' catch rates after accounting for vessel characteristics and other inputs [2, 23, 87, 106, 168, 169, 235]. Researchers have specified proxy variables for the age, education, and experience of managers or principal components analysis of personal characteristics of managers to derive a proxy variable for management. Comitini and Huang [46] and Campbell [35] employed dummy variables based upon one or more knowledgeable experts' subjective evaluations of ordinal levels of skipper skill. Holt [110] specified a cardinal measure of fishing skill, based on the proportion of successful pursuits adjusted for vessel characteristics and days of effort, designed to distinguish between professional and nonprofessional vessels. Del Valle et al. [53] used the ratio between the number of small landings and total landings as a measure of skipper skill. As with all proxy variables, measurement error and bias can follow, although the asymptotic bias expected from inclusion is generally smaller than from exclusion. Endogenous regressors with biased and inconsistent parameter estimates are also a danger.

Kirkley et al. [128] specified managerial efficiency or skipper skill as technical efficiency measured through a stochastic production frontier. Extending the technical efficiency approach, Kirkley et al. [128], Sharma and Leung [200], Vishwanathan et al. [246], and others included an additional equation explaining the technical inefficiency term. Such studies were often unsuccessful or inconsistent when attempting to explain technical inefficiency identified as skipper skill by variables such as years of education or experience.

Squires and Kirkley [219] applied the panel data approach of fixed and random effects for the combined effect of the vessel and skipper to distinguish productive performance between vessels. Wolff et al. [260] specified a three-way fixed effects model, distinguishing between the vessel and skipper fixed effect (along with time effects). They further allowed for potential time-varying firm management, whereby the skipper can learn through acquiring additional experience with the production process over time and through length of job tenure with a vessel or firm. Tingley et al. [238] utilized data envelopment analysis, along with the stochastic production frontier, to evaluate skipper skill.

Nonrivalrous Inputs

A vessel's production function depends not only on its rivalrous and excludable (i.e., private) inputs but also its nonrivalrous and (partially) nonexcludable inputs. The nonrival and (partially) excludable public good knowledge or ideas – new and accumulated technology – can be embodied in both physical and human capital of the fishing firm [221, 224]. Knowledge has an accompanying externality and social learning external to individual producers [12, 187]. A firm's production function then depends on the level of knowledge in the economy or fisheries sector. One firm's innovation, adopted by other firms, enhances all firms' productivity and innovation.

Nonconvexities arise with knowledge embodied in accumulated and new technology. Once the high fixed cost of creating new and better knowledge is incurred, the public good knowledge can be repeated at little or no additional cost [12, 187]. This generates increasing returns to scale external to the individual producer over all inputs – both rivalrous and excludable (private) and nonrivalrous and (partially) nonexcludable (public) – in the production function.

New sources of knowledge – new technology – can either arise exogenous to the sector, such as with information and communications technology embodied in electronic and other equipment to find fish, or can arise endogenously through research and development, such as biased technological change to reduce bycatch by reducing the bycatch-target catch ratio. In either case, this new technology becomes endogenous within the fisheries sector due to the producer's investment decisions required to implement it and the knowledge externality accompanying it. Knowledge can be accumulated indefinitely without diminishing returns to physical and human capital, leading to ongoing, endogenous economic growth in effort and pressures upon the natural resource stock. Knowledge embodied in K_t intensifies this process.

Resource Stock

The resource stock S, measured in biomass or numbers of fish, is not under the control of the individual firm, and hence is an exogenous technological constraint in a positive firm-level analysis rather than normative industry-level analysis [126, 206, 207, 209, 212]. In the fisheries stock-flow production technology,

$\partial\pi(W, P; K, S)/\partial S \geq 0$, i.e., an increase in S does not reduce restricted profits $\pi(W, P; K, S)$ and $\partial\pi(W, P; K, S)/\partial S = W_S$, i.e., the firm's shadow value for S. A similar interpretation can be given to environmental parameters, such as sea surface temperature, wind speed, etc. Similar considerations hold for the full static equilibrium profit function and the full and partial static equilibrium cost and revenue functions. S is treated like other quasi-fixed or fixed stocks such as K, except in a dynamic approach in which K (with adjustment costs) is treated differently than S.

Several specifications are possible for S [8, 15]. In cross-sectional studies, S is treated as fixed, common to all vessels and equally distributed spatially, and not explicitly specified. In time series, S times a series of cross-sections (pseudo-panel data) or panel data has been treated with indices of abundance or actual measures from population assessments [24, 56, 99]. In multispecies fisheries, aggregate biomass is typically specified, if it is specified at all, due to the multicollinearity that would otherwise arise. Dummy variables or time fixed effects are often specified, especially in short panels [26, 198, 199, 206, 207, 242–211]. Time dummy variables can capture not just S but also changes in disembodied technology, state of the environment, regulations, and other factors that change over time. Squires [212] and Pascoe et al. [175] used revenue shares to aggregate individual species measures of abundance into a composite index of abundance. When population assessments are unavailable, indices serving as proxy variables (with attendant issues of endogeneity and measurement error) are sometimes specified [8, 15]. Comitini and Huang [46] used catch per skate (a flatfish). Kirkley et al. [127] used a vessel's last tow's trips using a scallop dredge. Eggert [63] used overall average landings value and Pascoe and Coglan [171] specified average catch value per hour fished. Kirkley et al. [130, 131] used lagged average fleet-wide landings per unit effort. Similarly, Pascoe et al. [175] used average fleet-wide catch per unit effort during the season's first week. Andersen [8] showed that production estimates (here from DEA) differ whether a stock index is specified for each primary species based on catch per unit effort, one stock index is obtained from independent stock assessments for each of the primary species, or inclusion of one composite stock index for each observation is based on the independent stock measures and relative importance of the primary species. If such catch indices are not properly specified (e.g., lagged and/or fleet wide), endogeneity and identification and proxy variable issues can arise along with other limitations discussed by Andersen [8]. All approaches implicitly assume that S is constant (not appreciably depleted) over the specified time period.

The stock elasticity, $\partial\ ln\ Y_t/\partial\ ln\ S_t$, measures the impact of changes in S_t upon Y_t in a production function. Conventional wisdom holds that the stock elasticity is close to zero for pelagic stocks due to their schooling behavior [99, 240] and closer to one for demersal stocks due to their more even spatial distribution [193]. Limited empirical studies find cod and saithe's stock elasticity lies between zero and one, pelagic herring and albacore at unity, and anchovy at 0.39. Gordon and Hannesson [91] find that the presence and size of the stock effect depend upon the time period and overall state of technology.

Dual Representations of Technology

Squires [206–211], Kirkley and Strand [126], Dupont [56, 57], Bjørndal [24], and Bjørndal and Gordon [26] introduced the dual approach to econometrically analyze the vessel-level technology, using cost, revenue, and profit functions rather than the primal approach of the production function. The dual approach was accompanied by the introduction of flexible functional forms, such as the translog, normalized quadratic, and generalized Leontief, which allow less restrictive input and output substitution possibilities and biased technological change. The disaggregated dual approach opened up the possibility of many types of analyses consistent with other areas in industrial organization and production economics that were under development at the time.

The dual approach greatly facilitated examining the multiproduct firm by allowing disaggregated outputs and inputs and exogenous prices as regressors. Specifications were generally partial static equilibrium or short run, conditional upon K_t. The dual approach has been used to estimate optimal vessel size [26, 207, 210, 211] and optimal engine power and headrope length [175]. It also allowed researchers to examine product supply and product transformation possibilities [122, 126, 205–207, 209–211], input demand and input substitution possibilities [56, 206, 207, 209–211], the specification and testing of various types of joint production, output and input-output separability, quantity controls (including ITQs) through virtual prices and quantities and quota shadow prices (discussed below), capacity and capacity utilization, and the multiproduct cost structure for revenue and profit-maximizing firms [208, 210, 211, 216].

Product Transformation and Substitution Possibilities

The dual approach provides short-run Hicksian (net, compensated) and long-run Marshallian (gross, uncompensated) output supply and derived input demand price elasticities. Due to local Le Chatelier effects from the expansion effect, long-run or Marshallian elasticities are more elastic than short-run or Hicksian elasticities. Measures can also be obtained from directional distance functions equal to the difference between strong and weak output disposal with efficient production frontiers [194]. Most dual-based models show that own- and cross-price elasticities of output supply and variable input derived demand are typically inelastic across gear types, and cross-price elasticities indicate a mixture of substitutes and complements and inelasticity for both inputs and outputs. Some elastic responses have been found in the long run using Morishima elasticities.

Output transformation possibilities reflect “selectivity” and “targeting” ability [37, 38, 194]. Complementarity and substitutability and the degree of elasticity reflect vessels’ ability to change product or input mix as they change when, where, and how they fish, and ex ante they indicate how vessels might respond to changes in input or output controls and whether or not vessels might discard quota overages. Elasticities and product transformation and input substitution possibilities change with changes in S and environment, and change when, where, and how fishing occurs. Morishima elasticities of substitution are occasionally used [13, 142, 173, 174]. Differences in output disposability indicate limited output substitution possibilities [194].

Substitution between unrestricted inputs (outputs) and restricted inputs (outputs) can be evaluated by the elasticity of intensity [54]: $\partial \ ln \ X_i(W, P; K)/\partial lnK_k$, where k denotes a type of capital (or output) and a negative (positive) elasticity shows a substitute (complementary) relationship. Studies examining the relationship between currently restricted inputs (such as a limited allowable fishing days) and unrestricted inputs using the elasticity of intensity include Dupont [57] and Deacon et al. [51] – who along with Dupont [59] pay particular attention to the dissipation of rents, Pascoe et al. [175], Hansen and Jensen [103], and Squires [215] who evaluated the impact upon the elasticity of intensity from adding or dropping quantity controls under the virtual quantity framework. Dupont [57] shows inelasticity and complementarity between the restricted and unrestricted input (which limits rent dissipation that would otherwise occur with input substitution), while Hansen and Jensen [103] show slightly elastic substitution between restricted days and fuel and no relationship between restricted days and vessel (capital).

Structure of Multiproduct Costs

The firm’s (vessel’s) multiproduct cost structure is central to analyses of multiproduct industry structure and the impact of public regulation [20]. The multiproduct cost structure was developed under the behavioral hypothesis of cost minimization of a given, exogenous output vector. However, because multiproduct fishing vessels’ products are endogenous, Squires [207, 211] and Squires and Kirkley [216] retrieved the multiproduct cost structure from the information contained in the revenue and profit functions under the behavioral assumptions of revenue or profit maximization with endogenous outputs, where the costs are shadow costs with the revenue function.

Economies of scope measure the cost savings from producing multiple outputs rather than producing each separately when production is (almost) joint in inputs [20]. Scope economies derive from weak cost complementarities or fixed costs that do not depend on the quantities of outputs produced but do vary on which outputs are chosen (since that affects local cost complementarities or anticomplementarities) [20, 93]. Squires [207, 210, 211] and Squires and Kirkley [216] extend the measurement of scope economies, transray convexity, incremental and average incremental costs, and weak cost complementarities to revenue- and profit-maximizing firms with endogenous outputs using the revenue and profit functions. Empirical results find both economies and diseconomies of scope in fishing vessels, either by directly estimating from the cost, revenue, or (restricted) profit function or from cost complementarities [7, 15, 119, 207, 208, 210, 211, 216, 256, 258]. Economies of scope are largely found in trawl vessels (as expected) and diseconomies of scope are found in the surf clam and ocean quahog fleet (reflecting the spatial stock separation).

Product-specific returns to scale $S_i[Y]$ measure the change in costs through variation in the quantity of one product while holding other products' quantities constant [20]. Firms with increasing product-specific returns to scale have a cost incentive to expand the scale of production of this product and may become specialized in its production. Squires and Kirkley [216] develop and show how to measure $S_i[Y]$ and incremental and average incremental costs for the revenue or profit-maximizing firm. A sufficient condition for $S_i[Y]$ can be obtained by examining incremental marginal shadow costs or costs found from the diagonal elements of the Hessian submatrix for outputs from the estimated parameters of the profit or revenue function [207, 210, 211, 216]. Empirical results indicate that different pelagic and demersal species are produced under conditions of both increasing and decreasing product-specific economies of scale [7, 15, 55, 119, 199, 207–211, 216, 256]. Some species, such as those long lived and slow growing, which are subject to increasing product-specific returns, can be vulnerable to overharvesting due to the decreasing marginal production costs.

Multiproduct economies of scale are typically measured along a ray in output space that keeps outputs in fixed proportions, although other measures exist [20, 198]. The revenues exceed, are less than, or equal to (long-run) costs as there are decreasing, increasing, or locally constant long-run ray returns to scale. Increasing multiproduct returns to scale are found by Hannesson [99], Bjørndal [24], Asche et al. [17], Weninger [256], Bjørndal and Gordon [27], Felthoven and Paul [76], Nesbøkken [164], and Lazkano [142] and decreasing multiproduct ray returns to scale are found by Squires [206–209], Squires and Kirkley [216], Alam et al. [7], Horace and Schnier [112], and Hoff and Frost [107]. Increasing multiproduct ray economies of scale are sometimes found in output-regulated fisheries that prevent vessels from increasing the scale of production.

A cost function is subadditive at an output vector Y if and only if it is lower cost to produce Y than to produce the outputs comprising Y individually, i.e., $C(Y) \leq C(Y^1) + C(Y^2)$ [20]. Evans and Heckman [68, p. 615] stated: "Thus an industry is a natural monopoly if a single firm can produce all relevant output vectors more cheaply than two or more firms." Cost subadditivity would suggest that some form of fishermen's monopoly is appropriate on private efficiency grounds [167, 210, 211]. Squires [207, 211] develops local sufficient conditions for cost subadditivity using revenue or (restricted) profit functions. Onofri and Francesc [167] devise an additional test for cost subadditivity in the fishery sector. Squires [211], Alam et al. [7], and Onofri and Fransesc [167] reject cost subadditivity in fishing industries. Decreasing multiproduct ray economies of scale would explain the absence of cost subadditivity.

Multiproduct Joint Production

The nature of joint production, including the production possibilities frontier (PPF), impacts model specification, spatial management, rights-based management, and fisheries management in general. Changes in S_t shift the PPF in or out and twist it in the stock-flow production process. Area fished does not alter the PPF (except in a disaggregated model in which different areas contain different resource stocks). Different areas, aggregations by age and size, etc. are readily accommodated under block joint production as discussed below. Here we only discuss desirable products and the most relevant types of joint production for desirable two species (products) Y_1 and Y_2.

Joint-in-input quantities production arises when all inputs are used to produce all outputs [98, 140]. The PPF implicitly assumes either a reasonably homogeneous distribution of both species across all fishing grounds or aggregation across such areas. Many of the ex ante analyses discussed above specified and tested this type of PPF. This PPF could also be applied to outputs specified as species area and to completely different resource stocks (and hence areas) as in Holzer and De Piper [111]. If only some of the species are regulated by transferable quotas, substitution from regulated to unregulated species may occur [16, 58, 66, 189]. Squires and Kirkley [218] developed the two-price, two-quantity direct elasticity of transformation for two ITQ-regulated species and this type of jointness.

Almost joint-in-input quantities arises when the production process uses not only standard inputs such as fuel and labor but also quasi-public inputs, especially the vessel K_t that cannot be explicitly allocated among nonjoint production processes [141, 146]. Many of the ex ante analyses were short run in K_t and hence almost joint-in-input quantities. Pascoe et al. [173] applied this approach in a multiproduct distance function, and Hutniczak et al. [118] specified a restricted profit function. Hansen and Jensen [103] recognized the issue of almost jointness, but specified a distinct and unique model using days as an input and a multistage production process.

Nonjointness-in-input quantities [98], also called output independence [138, 139], arises when: (1) there are separate production processes for each harvested species or areas and (2) inputs are allocated between the different production processes. Each production process can be separately regulated without affecting production of the other processes because there are no technological or cost trade-offs between the output of one activity and that of another [126, 205, 207]. No empirical study has found nonjointness-in-input quantities in fisheries throughout the species set.

Different multiproduct production processes can even be scalar multiples of one another when there is either Leonteif aggregation of inputs and outputs, so that they are in fixed proportions, or a single input and output (homothetic input-output separability and nonjointness-in-input quantities). This is the specification of linear programming, which Reimer et al. [184] utilized for different areas. Each product combination is produced in fixed proportions, and hence there are not changes in product-species compositions for an individual production process. Instead, changes in species mix arises through shifting to a different production process (which could pertain to different area or gear type).

Block jointness in inputs [33, 34, 134], also known as block output independence [138, 139] and first discussed in fisheries by Squires [204], arises when there are multiple but distinct and separate production process that are joint among a range of production of products but nonjoint between these processes. Squires and Kirkley [216] found block jointness for Pacific coast groundfish trawlers.

Two forms of joint-in-input quantities production that directly addresses area and area-specific species combinations or simple species aggregations for interrelated species or sequential production of different species, species groups, or gear configurations is a block structure and almost jointness [146]. Hence, individual species (or groups of species) could be partitioned into joint blocks (i.e., groups) that capture product-species combinations and or product-species groups and areas (which can be a simultaneous decision, since area often defines species composition and density) or different gear configurations. For example, two separate fishing grounds for species groups Y_1 and Y_2, in which there are product transformation possibilities within each block but not between blocks.

The block joint, almost joint, and nonjoint-in-input quantities specification could be combined with a multinomial logit/probit model [35] or switching regression, or random utility model [29] for choice of area, depending upon the vessel's behavioral assumption. Alternatively, products species could be explicitly defined by area species and three-way panel data specification to also allow for endogeneity in both area and species [112]. Area dummy variables as regressors could potentially be biased and inconsistent since they are potentially endogenous due to the choice of fishing ground.

Almost joint-in-output quantities [140, 141] arises when there are multiple production functions for each type of variable input with the exception of sharing the fixed inputs. Such jointness can imply the sequential use of different inputs or different fishing strategies as found by Hutniczak et al. [118]. Allocated fixed inputs can create product interdependence that differs from technical interdependence. Hansen and Jensen [103] develop a restricted profit function with allocable days which is also discussed by Reimer et al. [184].

Empirical tests for gill net, trawl, purse seine, longline, and dredge vessels almost always reject nonjointness in inputs or almost nonjointness-in-input quantities [7, 13, 15, 55, 118, 126, 173, 189, 199, 206, 207, 236]. Exceptions include Campbell and Nicholl [38], who find nonjointess for generalist firms and nonjointess for purse seine vessels (specialized firms), Squires and Kirkley [216] who find nonjointness for one product and reject nonjointness for all others in a trawl fishery (giving a block joint production process), Weninger [256] for the ocean quahog and surf clam fishery, and Alam et al. [6] who find both input-output separability and nonjointness in a Malaysian gillnet fishery, which implies that all supply equations are scalar multiplies of one another [98].

Separability

Aggregation of individual outputs, notably individual species, into a single output and inputs, such as capital, fuel, and labor (L) into a composite input effort (E) is the structure of the bioeconomic model. Aggregation occurs through either Leontief-Sono separability, Hicks-Leontief aggregation, or the generalized composite commodity theorem [28, 143]. Input-output separability is the implicit structure of the bioeconomic model, in which there is a single composite input and output, and the marginal rate of transformation between outputs is independent of changes in inputs, and the marginal rate of substitution between inputs is independent of changes in outputs [99, 207]. Only the levels of catch and effort require regulation, and regulation of the input (species) mix does not adversely affect the optimal product (factor) combinations [207]. Input-output separability has largely been empirically rejected [7, 13, 37, 38, 55, 118, 126, 173, 189, 207, 210, 211, 216, 256]. Two notable exceptions are Alam et al. [6] and Squires [206] who did not reject input-output separability.

Distance Functions

The distance function starts from a set-theoretic foundation and does not require a specific functional form in contrast to the production function. Distance functions also allow specifying disaggregated outputs and inputs in the primal rather than the dual specification. Distance functions have been used to estimate technical efficiency [127, 128, 258, 180, 181], capacity [60, 124, 125, 126, 129, 145, 247], productivity [76, 166, 252, 255], vessel valuation [75, 130, 131], targeting and bycatch problems [72, 173, 174, 194], vessel buyback programs [250] and optimal fleet size and the basis for vessel buyout programs [132, 250]. Dupont et al. [60] and Herrero et al. [104] included slack variables into DEA models to allow for non-radial changes in input and output mix. Walden and Tomberlin [249] introduced an "order-m" frontier and free disposal hull to estimate fishing capacity [251].

Technical efficiency refers to the individual firm or vessel's level of production given its bundle of rivalrous inputs, and states of technology, environment, and resource stocks, relative to the best-practice frontier established by the highest achieving firms or vessels. Technical efficiency from an input orientation is $TE_I(y,x) = 1/D_I(y,x) \leq 1$, where $D_I(y,x)$ denotes an input-oriented distance function. The TE_I value indicates the amount a vessel will have to scale their inputs downward it be technically efficient and operate on the best-practice production frontier. If an output orientation is desired, TE is given by $TE_o(x,y) = [D_o(x,y)]^{-1} \geq 1$, where $D_o(y,x)$ denotes an output-oriented distance function [85]. A natural extension of measuring TE was the estimation of vessel capacity using the Johansen [121] plant capacity definition. The introduction of data envelopment analysis (DEA) [41] and the stochastic production frontier (SPF) [5] were pivotal in using distance functions to model vessel-level production.

Although these methods were introduced before 1980, it took some time for fisheries researchers to integrate them in their work.

The directional distance function, a generalization of the traditional distance function, can be used to account for unintended outputs, such as bycatch. This modeling of TE measures a vessel's ability to expand its intended catch and contract its bycatch given their input use. Such models to estimate vessel productivity and TE include Weninger [257], who modeled the efficient production frontier for vessels operating in the mid-Atlantic surf clam and ocean quahog fishery. Scheld and Walden [194] examined TE for multispecies fisheries where the ability to catch one species may be hindered due to regulations regarding catch of other species. The stochastic multiproduct distance function has also been estimated to evaluate output transformation possibilities in fisheries [81, 173, 174, 176, 184].

Technical Efficiency and Stochastic Production Frontiers

The stochastic production frontier is the most widely used specification in fisheries to measure technical inefficiency or deviation from the best-practice frontier. The stochastic production frontier relates a vessel's maximum output given inputs, $X_{1it}, X_{2it}, \ldots, X_{Nit}$ while allowing for stochastic events. A second, simultaneously estimated equation can explain the technical inefficiency according to exogenous or predetermined variables.

Hannesson [99] applied the first production frontier, a deterministic one and to Norwegian cod fisheries, in which the one-sided deviation from the frontier captures both stochastic shocks and technical inefficiency. Kirkley et al. [127, 128] followed with the stochastic frontier, identifying technical efficiency with skipper skill (see the skipper skill section). These early papers specified only the production frontier. Sharma and Leung [200], Vishwanathan et al. [246], and Squires et al. [226, 228] first included the second equation to explain technical inefficiency. Grafton et al. [94] 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. Kompas et al. [133] first related technical inefficiency to input controls, showing that technically efficient fishers substituted unregulated for regulated inputs and that technical efficiency declined with increasing restrictions on production. These and many other studies that followed find different degrees of technical inefficiency, and those relating technical inefficiency to measurable attributes of skippers and crew find a wide range of results but typically do not find a statistically valid relationship. Asche and Roll [14], using a shadow revenue function, estimated revenue inefficiency and its decomposition into technical and allocative inefficiency in the Norwegian groundfish fishery. Horace and Schier [112] introduce time-varying technical inefficiency through nonparametrically identifying time-varying technical efficiency by exploiting the spatial variation of vessels in three-dimensional (cross-sectional, time, and area) panels in Berring Sea flatfish fisheries, where each cross-sectional vessel can move across space and time.

Recent analyses focused upon the impact of rights-based management upon technical efficiency. New [162] found that structural adjustment reducing fleet size did not impact vessels' technical efficiency in the Australian Eastern Tuna and Billfish Fishery. Schnier and Felthoven [196] found that a vessel's measure of technical inefficiency is a significant and positive factor in explaining whether it exits a fishery following ITQs. Huang et al. [114] found that participation in the collective rights-based management system ("sectors") of the New England groundfish fishery impacted behavioral responses rather than technical efficiency even though sector participation led to shifts in the production frontiers for trawl and gillnet vessels. Estrada et al. [67] examined the impact on technical efficiency of cooperative catch shares for artisanal vessels in anchovy and sardine fisheries in south-central Chile using a difference-in-differences causal inference framework. The cooperative catch shares reduced average technical efficiency, although the impact on heterogeneity depended upon the characteristics of fishermen's organizations, so that greater cooperation among members increased technical efficiency. Mainardi [149] specified and estimated two stochastic frontier semiparametric models for a panel of Falkland Island fisheries over 2003–2014 that treat unobserved heterogeneity as a finite mixture or discrete approximation to continuous parameter variation, by adjusting for sample selection and latent classes, respectively. The hypothesis of frontier-enhancing effects of the new ITQ/ITE regime is supported for most, albeit not all, fishing companies. Evans et al. [69] estimate a cost frontier with time-varying inefficiency to allow for spatial variation in unobserved productivity effects and measure changes in technical efficiency, capital investment/divestment incentives, and resource rent following ITQs.

Other approaches can measure TE. Salvanes and Steen [190] specified a thick frontier, in which the best-practice frontier is determined by grouping together vessels with the smallest estimated disturbances. Holloway et al. [109], Holloway and Tomberlin [108], and Tomberlin and Holloway [239, 240] apply the Bayesian approach to composed error models under alternative, hierarchical characterizations, and demonstrate the Bayesian approach to model comparisons using recent advances in Markov Chain Monte Carlo methods. Collier et al. [44] evaluate a California multiple-input, multiple-output fishery using a hybrid DEA stochastic frontier model in which DEA is used in a first stage to measure aggregate output used in the second stage, the stochastic production frontier. Pascoe et al. [175], estimating a restricted multiproduct profit function, applied the fixed effects approach of Schmidt and Sickles [195].

Rationing and Quotas

The microeconomic theory of quotas, rations, and other quantity controls allows better understanding of their impact upon fishing vessels. These quantity controls include nontransferable individual vessel quotas and individual transferable quotas (ITQs) for catch and effort and limits on gear, fishing time, vessel size, and inputs in general.

The microeconomic theory of rationing and quotas for firms, initially developed in consumer theory [161] and international trade [160], was extended to production theory by Fulginiti and Perrin [86], Squires and Kirkley [216–218], Segerson and Squires [199], Squires [213, 215], Squires et al. [225], Vestergaard [243], and Vestergaard et al. [245]. Using the virtual price framework of Neary and Roberts [161], Squires and Kirkley [216–218], and Squires [215] showed that the unit rent of an individual transferable quota, or ITQ, is the difference between the output price and virtual price of the quota and forms the firm's inverse derived demand function for the ITQ. Firm inverse demand is horizontally summed to form the market ITQ demand. In equilibrium, the horizontally summed aggregate inverse ITQ demand curve equated to the exogenous aggregate supply curve (typically a total allowable catch or effort) gives the market ITQ price. The Antonelli matrix of changes in endogenous unit rents in response to exogenous marginal quota changes gives this unit rent and forms the basis of ITQ price flexibilities. Squires and Kirkley [218] also calculated the gains from trade, estimated the ITQ product transformation frontier, and developed the direct elasticity of substitution (two price-two output) between ITQs. Extending Neary's [160] ex post framework using virtual quantities – the dual to virtual prices, Squires [214, 215] evaluated the effects of adding, subtracting, or changing existing quotas. The microeconomic theory of rationing and quotas addresses the substitution of unregulated inputs for regulated inputs in input-regulated fisheries, first described by Pearce and Wilen [179] and Wilen [259], by Squires [206, 213–215] and Dupont [57] and to the spillover effects between quota (including ITQ)-regulated species and unregulated species [16, 58, 66, 117, 215].

Le Chatelier Principle, Quotas, and Product Transformation Possibilities

The Le Chatelier principle as applied to economics by Samuelson [191] shows that there are behavioral implications of rationality which are only exhibited when extra constraints are imposed or withdrawn. The Le Chatelier principle applies when transitioning from short-run to longer-run production or adding or subtracting or adjusting quantity controls, such as quotas or trip limits, or property rights or other direct regulations that impact production. The local Le Chatelier principle states that if variables in a system are chosen to optimize a function, then as a result of an infinitesimal (i.e., marginal) change to the system, e.g., an extremely small change in prices or quotas, the responsiveness of the chosen variables will be reduced (increased) when extra constraints are added to (dropped from) the optimization problem. The Le Chatelier principle can be local, corresponding to marginal changes, or global, corresponding to nonmarginal changes [155]. The key question is whether the change in production is due to a nonmarginal (discrete) rather than marginal (infinitesimal, local) policy shock.

The Le Chatelier principle can explain the failure of ex ante analyses in fisheries to consider the full range of a vessel's ability to adjust its catch and/or input mix when there are nonmarginal (discrete) changes in policy, production constraints, industry structure, markets, biology, environment, or prices. Squires and Kirkley [216–218], Squires et al. [227], and Pascoe et al. [173, 174] ex ante analyzed the introduction ITQs in multispecies fisheries. Appealing to the local Le Chatelier principle, they observed that ITQs may be ineffective due to limited substitution possibilities between species, leading to potentially high discards or difficulties in quota balancing. However, Sanchirico et al. [192], Branch and Hilborn [30], Abbott et al. [1], Reimer et al. [184, 185], and Scheld and Walden [194], through ex post empirical evaluation of multispecies fisheries with ITQs compared to production prior to ITQs, found that vessels can frequently adjust their species mix far easier than the ex ante analyses incorrectly anticipated. A global meta-analysis of 345 stocks showed that for many fisheries, management controls improve under ITQs in terms of reduced variation in catch around quota targets [154], although counter-evidence also exists [135]. ITQs can also reduce bycatch [62].

Reimer et al. [184, 185] posit that the estimated model must be "structural" with respect to that shock, as discussed by Haavelmo [97] and Lucas [147] for economics in general and for rights-based management in particular. That is, the ex ante analyses' assumptions of invariant behavioral equations are inconsistent with dynamic maximizing behavior and changed incentives. Reimer et al. [184, 185] observe that revealed production possibilities are frequently constrained and confounded by regulatory incentives, and that the empirically revealed production set strongly depends on the institutional, economic, and biological setting in place when fishing was observed.

The Le Chatelier principle more rigorously explains the failure of ex ante models to anticipate vessels' responses to introducing rights-based management. When rights are introduced and existing direct regulations are reformed in marginal ways, then the local Le Chatelier principle applies. Rights, however, are often introduced into a deteriorated fishery and replace existing and highly restrictive direct regulation or lead to its substantial modification. This situation constitutes a nonmarginal policy shock and a change in complementary institutions, regulations, and business practices, whether or not the property rights as transferable output controls are simply marginal extensions of the existing regulations. The global Le Chatelier principle framework then fully explains the observed results of greater flexibility and is consistent with economic theory.

Fishing Time

A tension can exist between the standard economic approach to production, which specifies variable inputs by some physical capital, notably gear and equipment, and labor, materials, and energy, and the standard biological specification of days as steaming, search, and fishing time. (A few studies examining fisheries regulated by days, in which case days were specified as quasi-fixed. These studies include Dupont [56, 57] and Hansen and Jensen [103]. The use of days to represent variable inputs represents use of a proxy variable as a flow of energy and services from stocks of labor, gear, and equipment. Proxy variables can introduce measurement error, in turn leading to biased and inconsistent parameter estimates. Days as a variable input in an econometric model can also be subject to endogeneity and identification issues, in turn also leading to biased and inconsistent parameter estimates. The use of days, depending upon its application, can implicitly assume either Leontief aggregation or homothetic input separability.

Another tension exists between the stock of physical capital K and labor L and flow of capital and labor services. When K and L are specified as fixed or quasi-fixed factors, then production is conditional upon these stocks and issues do not arise. When K and L stocks are specified as variable inputs, then the implicit assumption is made that flows are proportional to stocks. When this assumption is invalid, then biased and inconsistent estimates potentially arise due to the measurement error.

Technological Change

Technological change is one of the main driving forces behind the historical development of fishing industries. Along with investment in K_t, technological change impacts the status of the resource stocks and the extension of fishing grounds by depth and geographical range, broadening of species harvested, and habitat impact. Population biology addresses technological change through time-varying catchability and changes in selectivity. Technological change can be: exogenous, endogenous, or both, oriented on the process (inputs) through process innovation (and factor augmentation) or outputs through product innovation (and product augmentation); disembodied or embodied; and centered on target species or bycatch species. Technological change can be oriented to the target species or desirable outputs, the conventional approach. Technological change can also be oriented to bycatch or habitat impact or undesirable outputs, which is biased technical change. More generally technological change can be either neutral (typically Hicks neutral) or biased in the outputs or inputs. Technological change can lead to lower costs per unit of effort (input augmenting) or increased catch rates per unit of effort (output augmenting) given S_t. Technological change can also lead to new species caught through expanding the range of production and introducing new areas and depths to fish with new gear and equipment.

Technological change on target species and input usage is largely exogenous to the fisheries sector [221, 222, 224]. Endogeneity arises through any investment in physical capital, by which the technological change is embodied, or for research and development to adopt the external sources of new technology to fisheries. Technological change to reduce bycatch and habitat impact is largely endogenous to the fisheries sector. Endogeneous technological change arises because technological change typically requires research and development. Further endogeneity arises if the new technology is embodied in new physical capital requiring investment. Measurement of technical change in fisheries is typically based on primal specification of technology, notably the production function, or cost diminution given output (dual), over time [46, 130, 131]. Economic analysis of technological change essentially treats it as a residual after all other inputs and control variables (technological constraints) have been included in the model [204], including the resource stock [212].

The most common specification of technological change in fisheries production functions is disembodied and accounted for by a linear time trend, which implicitly assumes that technological progress is Hicks neutral, exponential, and progresses at a constant rate [46, 65, 80, 99, 110, 156, 158, 175, 201, 221, 224]. Pascoe et al. [175] find a positive linear time trend and negative squared linear time trend, indicating increasing Hicks-neutral technological change but at a declining rate. Hannesson et al. [102] adopted the approach of Baltagi and Griffin [18], which allows technology to progress at a variable rate for each individual year, to evaluate technical change over 100 years in the Lofoten cod fishery and extended by Kvamsdal [137]. Gordon and Hannesson [91] applied an ARMAX model to the Norwegian winter herring fishery. Banks et al. [19] and Kirkley et al. [130, 131] analyzed embodied technical change in the Sète trawl fishery using dummy variables. Kvamsdal [136] applied a structural time series model with a stochastic trend to measure technological change in a Cobb-Douglas production function with both single equation and multivariate models to the Norwegian Lofoten cod fishery. Fissel and Gilbert [79] specified a compound Poisson process incorporated into the catchability coefficient of the Schaefer production function. Gilbert and Yeo [89] examined technology adoption patterns and productivity differences in a Malaysian artisanal fishery to evaluate whether technology is a substitute or complement for managerial skill, i.e., examining skill-diluting and skill-augmenting technological change.

Productivity Growth

Measurement of total factor productivity (TFP) growth in fisheries requires accounting for all the sources of growth to disentangle changes in the TFP residual from changes in S_t and the environment. This section surveys measuring TFP growth using the growth accounting framework of Solow [204] and economic index numbers as opposed to econometrically estimating technological progress using a production function to then infer productivity growth. Walden et al. [254] give an additional survey of productivity change in fisheries.

Bell and Kinoshita [22] measured labor productivity and Kirkley [122], Norton et al. [163], and Davis et al. [50] estimated TFP in a growth accounting framework but without accounting for changes in S_t. Squires [208–213] and Herrick and Squires [105] specified a growth accounting framework using economic index numbers and recognized the stock-flow nature of the production technology to disentangle changes in S_t from inputs changes, while adjusting for $S_t{}'$ s elasticity of output and variations in capacity utilization under both open access and the economic optimum (sole owner). Squires [212, 213] developed superlative index number approaches to consistently aggregate the resource stocks of individual species into an aggregate S. Jin et al. [120], Arnason [11], Hannesson [101], Torres et al. [241], Eggert and Tveterås [64], Pan and Walden [170], and Walden et al. [255] analyzed TFP growth in different fisheries. Brandt [31], Walden et al. [252, 253], Färe et al. [74], Solís et al. [203], and Thunberg et al. [237] evaluated the impact of ITQs upon TFP growth. Felthoven and Paul [76], Squires et al. [229], and Paul et al. [178] accounted for changes in the state of the environment. Squires and Vestergaard [223] developed the impact of TFP growth on optimum resource use within the context of the bioeconomic model. Pascoe et al. [177] further discuss the impact of productivity growth (and TE) on maximum economic yield.

Norton et al. [163] developed an index of profits or economic health that incorporated TFP, but not accounting for changes in S_t. Fox et al. [83] fully decomposed a profitability index, which included price, productivity, and capacity utilization indexes and changes in S_t, to determine whether changes in productivity or prices have the largest impact upon profitability change. Subsequent profitability index analyses include Dupont et al. [61], Fox et al. [84], and Walden and Kitts [248].

Two broad approaches have been used to construct economic index numbers [254]. The first approach used constructed superlative economic index numbers using prices as indicators of production elasticities in the Lowe, Törnqvist, and Fisher ideal index numbers. Economic index numbers can also be constructed using distance functions and linear programming. These methods construct a production frontier based on observed values of inputs and outputs in different time periods, which also allows decomposing productivity change into change in technical, allocative, and scale efficiency. Some of the different indices that can be constructed include the Malmquist, Hicks-Moorstein, and Lowe.

Bioeconomic Models

Effort as an Input

Early bioeconomic models specified an aggregate production function coupled with a biological model [90, 197, 202]. These early models, which grew out of biological production models, typically specified a single composite rivalrous input "effort," E [49, 99, 126, 188, 206, 207]. Effort in biological models usually involved a time component, such as days absent from port, or time the gear was in the water.

Huang and Lee [113] and Anderson [9, 10] were among the first economists to question the biologists' specification of effort. Anderson [9, 10] specified effort as the output of a two-stage production process, although not founded upon theory (Leontief-Sono homothetic separability or Leontief aggregation, exact separability, and aggregate production functions). In contrast, Huang and Lee [113] discussed effort within the context of separability and aggregate inputs and the conditions for an aggregate production function. They specified the aggregate production function in terms of individual inputs K and L rather than composite E. Anderson [9, 10], interested in individual firms' production functions but retaining E, constructed cost curves based on E. Hannesson [99] provided a theoretically consistent framework of separability and aggregation to composite E and defined a more general production framework that integrated E with traditional neoclassical production theory.

Multiproduct technologies have a comparable two-stage optimization process in which revenues are optimized in each stage of aggregation and with allocative efficiency to form the composite output Y_t [206, 207, 221, 224]. The separability is exact, rather than approximate, since $Y_t = f(q, E_t, S_t)$ is an exact representation of technology. Weak (and therefore also strong) Leontief-Sono separability is not a sufficient condition for the first stage of aggregation. Homothetic separability provides both a necessary and sufficient condition, which requires a linearly homogeneous aggregator function [28, 92, Lemma 3.3a]. Linear homogeneous E_t aggregator functions for the rivalrous inputs, $E_t = g(X_{1t}, K_t)$, satisfies Fisher's factor reversal test, in which the cost of the rivalrous inputs equals the product of $g(\bullet)$ and the corresponding implicit price index [77]. (To simplify notation, let X_{1t} denote a scalar composite of variable rivalrous and excludable variable inputs and let K_t denote the scalar composite of rivalrous and excludable nominal physical capital stock in natural units, i.e., not in efficient units.) K_t is aggregated over different individual units of capital of different vintages and levels of embodied capital according to specific conditions [78]. Linear homogeneity of $g(\bullet)$ in rivalrous inputs also satisfies the replication argument of production functions with rivalrous inputs [187]. Linear homogeneity in $g(\bullet)$ in rivalrous inputs gives the familiar Graham-Schaefer production function in which the exponent of E_t is linear: $Y_t = qE_t^1 S_t^\beta$.

Leontief aggregation requires: $E_t = \min(AX_{1t}, BK_t)$, where A and B are fixed coefficients and in which one of X_{1t}, K_t is the limiting factor [3, 113]. Allowing for embodied technical change in K_t, $\tilde{E}_t = \min(AX_{1t}, B\Psi_t K_t) = E_t = \min(AX_{1t}, J)$ [221, 224]. Either X_{1t} or J_t ($J_t = \Psi_t\ K_t$), i.e., K_t in efficiency units, where the average embodied technical efficiency, Ψ_t, is defined as the weighted average level of best-practice efficiency associated with each past vintage of investment, will be partially idle in the sense that a small change in one input will not affect output or factor prices. There will be historical partial surplus of either X_{1t} or J_t. The more general Hicks-Leontief composite commodity theorem requires that the ratio of input prices or quantities of individual rivalrous inputs comprising E_t to the composite effort price or quantity is independent over time [143]. The standard fisheries bioeconomic model often assumes the more restrictive Leontief aggregation [43]. Specification of days as effort implicitly assumes one of these forms of aggregation (homothetic Leontief-Sono, Leontief, or the Hicks-Leontief composite commodity theorem) and forms a proxy variable.

With homothetic Leontief-Sono separability for rivalrous inputs and embodied technological change, $\bar{\bar{\bar{E}}}_t = f(X_{1t}, \Psi_t K_t) = f(X_{1t}, J_t)$ and $J_t = \Psi_t\ K_t$ are themselves aggregates in full static equilibrium [221, 224]. As a linearly homogeneous function, $\bar{\bar{\bar{E}}}_t$ can be written as $\bar{\bar{\bar{E}}}_t = \Psi_t f(\frac{1}{\Psi_t} X_{1t}, K_t) = \Psi_t \bar{\bar{\bar{E}}}_t$. Assuming a constant rate of embodied technical change ψ and constant capital share of income M_2 with Cobb-Douglas functional form for production function $f(\bullet)$ implies that $\Psi_t = e^{M_2 \psi_t}$, where the growth rate of Ψ_t is ψ_t [115].

When the production technology is Cobb-Douglas or its Graham-Schaefer form (exponents of one for E_t, S_t), and the production technology is an exact representation of technology, then separability inflexibility, a restriction on the technology, is required (Proposition 1 of Denny and Fuss [52] and Blackorby et al. [28]). That is, the technology must be a Cobb-Douglas production function $f(\bullet)$ with a translog effort aggregator function $g(\bullet)$ or $f(\bullet)$ must be translog and $g(\bullet)$ Cobb-Douglas. Hicks-neutral, disembodied technical change independent of the rate of rivalrous K_t formation can be specified as growing at a constant exponential growth rate λ.

Nonconvexities arise with knowledge embodied in accumulated and new technology, creating dynamic increasing returns to scale external to the individual vessel over all inputs, both private and (partially) public, in the production function (as discussed above). Endogeneity is created because the dynamic increasing returns to scale are external to the individual production unit. This dynamic positive externality continously lowers unit costs with knowledge adoption, which incentivizes further adoption of new technology, and thus the endogeneity.

The aggregate production function can be specified with disembodied and embodied technical change, knowledge spillovers accompanying this technical change, and homothetic exact Leontief-Sono separability [221, 224]. Effort is then an unobserved composite, private (rivalrous) input. Endogenous nonrival knowledge spillovers, measured by $\theta > 0$, gives aggregate effective effort $K_t^{\theta} E_t^{\beta_1}$, which in turn gives $\beta_1 + \theta > 0$ and increasing returns to scale external to firm i in time t. Firm $i^{'}$ s output in time t with homothetic exact Leontief-Sono separability is $Y_{it} = \Lambda\left(J_t, t\right) \Psi_{it} f\left(\frac{1}{\Psi_{it}} X_{1it}, K_{it}\right) S_t^{\beta_2}$. Assume additive seperability across all firms i to give an aggregate technology. Let $\Lambda\left(J_t, t\right) = \Lambda(t) J_t^{\theta} = \Lambda(t)(\Psi_t K_t)^{\theta} = \Lambda(t)\Psi_t^{\theta} K_{it}^{\theta}$. Letting $\Psi_t = e^{M_2 \psi_t}$ and $\Lambda(t) = qe^{\lambda t - \mu(t,Z)}$, where q denotes the catchability coefficient, gives $Y_t = qK_t^{\theta} E_t^{\beta_1} S_t^{\beta_2} e^{(\lambda + M_2(\theta+1)\psi)t - \mu(t,Z)}$. For the Graham-Schaefer specification, $\beta_1 = \beta_2 = 1$. Absence of the external effect, $\theta = 0$, gives only rivalrous (private) inputs, giving $K_t^{\theta} = 1$ and $Y_t = qE_t^{\beta_1} S_t^{\beta_2} e^{(\lambda + M_2 \psi)t - \mu(t,Z)}$.

Firm $i^{'}$ s output in time t with Leontief aggregation builds off of Clark [43] specifying rivalrous E_t as the rivalrous stock of physical capital K_t formed under Leontief aggregation and K_t as the limiting factor [221, 224]. This allows for explicit, intentional, endogenous net investment in K_t, and $\beta_1 = \theta + 1$, $\theta > 0$, is the positive knowledge spillover, 1 is the rivalrous or private effect (each producer operates under the assumption of constant returns to the inputs that the producer controls), and β_1 is the aggregate effect. This specification assumes full capital and capacity utilization. The aggregate production frontier under Leontief aggregation for K_t as the limiting factor is written $Y_t = qK_t^{\theta+1} S_t^{\beta_2} e^{(\lambda + M_2(\theta+1)\psi)t - \mu(t,Z)} = qK_t^{\beta_1} S_t^{\beta_2} e^{(\lambda + M_2 \beta_1 \psi)t - \mu(t,Z)}$.

Both specifications allow for Debreu-Farrell economic (technical, allocative, and scale) inefficiency and disembodied technical change, learning by doing that can be exogenous and endogenous to net investment, and embodied technical change with accompanying knowledge spillovers and learning [224]. The Leontief aggregation specification of effort, in contrast to the homothetic Leontief-Sono separable specification of effort, explicitly explains, through endogenous and intentional net investment in K_t, how embodied technological change that originates from sources external to the sector and accompanying endogenous knowledge sillovers are endogenously introducted, through intentional investment in K_t, into the production process in the fishery sector. The homothetic Leontief-Sono separable specification provides a comprensive specification of rivalrous E_t using rivalrous X_{1t}, K_t and allows for input substitution as a source of endogenous growth, but does not account for intentional net investment. The Leontief aggregation specification assumes that rivalrous K_t is always the limiting factor without any input substitution as an endogenous source of growth.

Concluding Remarks

Production economics is increasingly important to the economic analysis and public regulation of fishing industries. Fisheries economics arose out of population dynamics and a focus upon the long-term dynamics of the natural resource stock and an aggregate production technology. These bioeconomic models aimed to obtain the optimum fleet size and resource stock. Production economics gained in importance as it developed as a field and was able to contribute to analyses of fishing industries with an industrial organization orientation and public regulation to address the market failure stemming from the common resource. This reorientation shifted the focus to shorter time periods and to the individual firm – usually the vessel – and to multiproduct, multi-input production. Other factors also contributed to the increased application of production economics to the fishing industry: (1) the development of large-scale data bases at the vessel level and econometric software and estimation procedures and (2) rapid development of production economics to address issues in other economic sectors and the general economy.

Empirical production analyses show that the individual vessel's multiproduct production process is typically joint-in-input quantities, that a consistent aggregate output or input seldom exists, and that input substitution and output transformation possibilities are typically inflexible or limited. Moreover, the longer the time period and adjustment of fixed or quasi-fixed inputs or even outputs, and notably the physical capital stock, the greater the input substitution and output transformation substitution possibilities due to the local Le Chatelier effect. Technical inefficiency is pervasive, sometimes ranging widely between vessels, allocative inefficiency exists, and technological progress is important. There is indeed skipper skill, but it cannot be readily explained by measurable factors.

Production economics in fisheries has come full circle to refine the specification of the original dynamic renewable resource economics (bioeconomic) models from which fisheries economics originally emerged. The concept of "effort" as an aggregate input used in early models has evolved substantially due to the general production economics literature. The theory of homothetic separability, aggregation, and index numbers makes clear that effort as a composite of rivalrous and excludable (private) inputs (capital, labor, energy, materials, etc.) is an index that requires consistent aggregation according to either Hicks-Leontief aggregation or homothetic Leontief-Sono separability. The homothetically separable effort aggregator function of nonrivalrous and excludable inputs is linear homogeneous and the exponent of effort is one. Allocative efficiency of the rivalrous inputs is accounted for in this effort aggregator function. The exponent of effort can exceed one when there is the nonrival input knowledge (due to technological progress) and fall short of one when there is congestion.

Technological change has often been overlooked in fishery economics and bioeconomic models, but is now more often incorporated, almost invariably as Hicks-neutral and exogenous.

When the public good knowledge, in the form of disembodied and embodied technical change, is incorporated into the production technology, the resulting knowledge spillovers require may create dynamic endogenous economies of scale in rivalrous and nonrivalrous inputs.

Fisheries economics now routinely addresses the stock-flow production technology through either specifying biomass, time trends, or dummy variables. Studies of total factor productivity growth disentangle growth in the productivity residual from changes in the resource stock. Productivity analyses are estimated from either econometrics and estimates of technical change or more likely growth accounting and economic index numbers. Many fairly recent studies have examined changes in total factor productivity due to the introduction of individual transferable quotas.

The impact of rights-based management, notably before and after and occasionally with counterfactuals of individual transferable quotas, is a major focus of analysis of production economics. The analytical approach has varied from estimation of multiproduct cost functions and frontiers, or stochastic or deterministic production frontiers, or measurement of total factor productivity growth through economic index numbers. One major finding is that product transformation possibilities become more flexible, due to local or global Le Chatelier effects as various previous direct regulations are lifted, thereby unbinding production possibilities. Technical and scale efficiency and total factor productivity tend to increase in most fisheries after the introduction of rights, although not in all cases, due to retirement of redundant capital, more efficient use of retained capital and other inputs, and quota transfers from less efficient to more efficient vessels. Local or global Le Chatelier effects clearly contribute. Most studies could not attribute causal inference since they were "before-and-after" rather than "with-and-without," where the "without" is modeled by a counterfactual. The length of industry adjustment following the introduction of rights-based management depends in part upon how many and to what extent and timing direct regulations, forming binding constraints, were relaxed or eliminated entirely, thereby impacting the local or global Le Chatelier effects.

Accounting for full economic efficiency, accumulated and new technology, and knowledge spillovers in bioeconomic models leads to a broader concept of the dynamic economically efficient equilibrium (i.e., maximum economic yield) than the original steady state and hence static scale efficiency. Since much of the ongoing technological change is in the form of information and communications technology originating external to the fisheries sector, when combined with knowledge spillovers, such a dynamic economically efficient equilibrium leads to dynamic increasing returns to scale, ongoing endogenous growth, and an optimum resource stock that is less than that of maximum sustainable yield.

Best-practice econometric estimation in fisheries production is improving over time. Attention is increasingly paid to identification issues, notably testing for endogenous regressors (such as effort), and when found instrumental variable estimation. Heteroscedasticity of a general nature is now routinely corrected through Eicker-Huber-White methods. Serial correlation receives less attention. The use of heteroscedastic-and-autocorrelation consistent standard errors, such as Newey-West or Driscoll-Kray, should be considered, given pervasive heteroscedasticity and serial correlation due to searching behavior. Spatial autocorrelation seldom receives attention. Panel data methods, notably fixed or random effects and their testing, are now well recognized. Addressing sample selection bias requires further attention, where this bias arises due to vessel entry and exit and the almost universal use of fishery-dependent data and nonrandom vessel search for catch. Moreover, fisher search is nonrandom or there can be gear saturation or density-dependent gear avoidance behavior. Sample selection bias is particularly important for bioeconomic models specifying an aggregate production function, since otherwise the results are not representative of the population and maximum economic yield is biased. Unit root and if necessary cointegration tests of time series of data, including panel data, for stationarity and degree of integration should become routine when the time series is sufficiently long; otherwise regression may be spurious and differencing may be necessary before further regression analysis.

Where do fisheries vessel-level production studies consistent with production economics head in the future? In the past, such studies largely followed new developments in production economics and econometrics, although the application of production economics to fisheries also contributed to further development of production economics, or by responding to the unique feature in fisheries of transferable property rights – essentially an application of quota and rationing theory. One topic that has received considerable attention is the spatial nature of production due to the area-based nature of fisheries production. Future analysis requires consistency with production economics and in particular the nature of joint production and separability. Block jointness-in-input quantities (block output independence) definitely requires further investigation and can contribute to incorporating area fished. When such a block structure is found, then a discrete choice model in the vein of Campbell [35] can be coupled with a primal or dual specification of technology. A comparable development arose in agriculture with allocable inputs. Random utility models of location can be made consistent with econometrics through identification and accounting for potentially endogenous inputs (such as distance or cost) as regressors, but face difficulty in pairing with production technologies (as in Campbell [35]) due to the objective function of utility maximization while production technologies with endogenous catch assume maximization of catch, revenue, or profit rather than utility.

Causal inference, including evaluating natural experiments, will grow in importance to evaluate policy. Explicit application of the local and global Le Chatelier principle can evaluate the impact of the transition from direct regulation to rights-based regulation. Accounting for bycatch and broader ecosystem impacts, which requires proper specification of joint production, is promising. Fisheries economics evolved from production functions with an aggregate output – a primal specification of technology – to dual-based methods and has shifted back to the primal problem but relying upon the directional distance function for a primal specification in part due to its accommodation of multiple outputs and joint production, including undesirable ones or public bads.

Analysis of technological change is yet another area. Most studies to date have specified Hicks-neutral disembodied and exogenous technological change at a constant rate measured through a linear time trend. Insufficient research has been conducted on technological change that is biased in either (desirable or undesirable) outputs or inputs. Endogenous technical change that is bycatch and habitat saving (directed technical change) has received little attention, and can draw from the considerable progress that has been made in general economics in this area. Little is empirically known about the factors that induce or direct biased technological change. Insufficient attention has been given to embodied technological change and the impact that different vintages of the physical capital stock, embodying different levels of technology, have upon harvesting. Similarly, research on investment, economic depreciation, and capital accumulation could receive additional attention.

Production economics can contribute to standardization of effort as practiced by population biologists. Standardization in fisheries refers to combining disparate technologies, each with different levels of productivity, into a single aggregate technology and composite input, effort, that in turn enters into a population model [152]. Topics within production economics that can contribute to standardization include consistent aggregation across technologies, firms, and inputs, frontier functions and economic efficiency (especially technical efficiency), multilateral and bilateral economic index numbers, joint production, and technological change that impacts time-varying catchability and could be biased. The related discipline of econometrics can contribute to identification strategies for potentially endogenous regressors in the catch-effort production technology and selection bias for fishery-dependent data. Econometrics can also contribute to standard errors when standardizing.

In sum, production economics in fisheries can both open up new areas of empirical analysis and contribute to theoretically consistent specification of production technology in both fisheries economics and population dynamics.

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