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# Productivity measurement in common property resource industries: an application to the Pacific coast trawl fishery

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*This article measures total factor productivity in industries that exploit resources held in common. Particular attention is paid to the valuation and specification of in situ common-property resources in a neoclassical production technology, catchability of the resource, and variations in economic capacity utilization. An empirical analysis of the open-access Pacific coast trawl fishing industry demonstrates that disentangling the productivity residual from changes in resource abundance, its catchability, and variations in capacity utilization hones the productivity residual to finer precision, lowering mean productivity growth by about half. Removing biological noise from highly variable resources is also important. The results are related to a program limiting the number of vessels and can contribute to sustainable resource management whenever resources are held in common.*

## 1. Introduction

■ In industries using common-property natural resources, productivity measurement faces the thorny problem of accounting for the nonpriced contributions from these resources. When changes in the abundance of the resource stock are not disentangled from measures of productivity or technical progress, results will be biased.[1]

The crucial factors for studies of productivity or technical progress in these industries are the proper specification and valuation of the common-property resources in a production technology and the related issue of market failure and external diseconomies to firms. In turn, these factors depend upon the structure of property or access rights, the level of aggregation of the analysis (the firm or society/industry), and the stock-flow relationship between the resource stock and its extractive activity. Smith and Krutilla (1982), Smith

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[1] Empirical studies of productivity growth or technical progress when resources are held in common neglected either the role of resource abundance, the issue of property rights and access, or recent advances in productivity measurement and economic index numbers. Squires (1988, 1991) reviews this literature.

(1980), Brown and Field (1978), and Fisher (1979) touched upon these concerns, but they have yet to be fully developed.

This article develops a framework for measuring total factor productivity (TFP) in industries that exploit renewable resources held in common, paying particular attention to the valuation and specification of resources in a neoclassical production technology. I modify the method of growth accounting and economic index number construction to accommodate the resource and to measure productivity growth in the Pacific coast trawl fishery. Accounting for changes in resource abundance, its catchability, and capacity utilization hones the productivity residual to finer precision, lowering it by about half.

Evaluating productivity growth in a common-property resource industry raises the issue of interpretation. Smith and Krutilla (1982) suggested that technical change or productivity growth in these industries can be a mixed blessing. It might merely hasten rent dissipation and resource decline beyond the economic optimum level—already exacerbated by excessive exploitation under open access. Yet the problem of superfluous inputs, made even more excessive through productivity increases or technical change, differs little from that of inputs made redundant in other industries. The key consideration may instead be a suitable program of public policies, rather than the absence of technical advance or productivity growth.

Sustainable resource use is also of increasing concern. Many of these resources are renewable and held in common, and their exploitation contributes to economic growth in a number of countries. Proper specification and valuation of these resources in production technologies are necessary before the appropriate economic research and policies can be formed or indices of economic growth, performance, productivity, or sustainability developed.[2] In addition, productivity-enhancing policies, coupled with sustainable resource management, boost profits and maintain cost competitiveness in global markets without resorting to temporary advantages from exploitation rates that are not sustainable at some optimum stock level.

Section 2 discusses specification and valuation of the common-property resource stock. Section 3 discusses the optimization problem for both the sole owner and open access, and it relates these results to corresponding total factor productivity measures. The effects of regulation, catchability of the resource stock, and capacity utilization are also evaluated. Section 4 describes the industry, data, and index number construction. Section 5 reports the empirical results, sources of technical change, and implications for license limitation programs. Section 6 provides concluding remarks.

## 2. Specification and valuation of the resource stock

■ Common-property natural resources traditionally have been treated like any other input in a neoclassical production technology. Beginning with Scott (1954), the common-property resource stock entered the production process as a factor of production and was treated as an asset, particularly as a stock of capital.[3] This approach was applied to both renewable and nonrenewable resources.

In an analysis rooted in the theory of the firm, it is inappropriate to treat a common-property resource stock as a conventional input. Instead, this stock is specified as a technological constraint on the individual firm's stock-flow technology because the stock's abundance affects the production environment within which firms operate but remains beyond

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[2] See El Serafy (1991), for example, for a parallel line of research on national income accounting. Ehui and Spencer (1990) develop an index of productivity and sustainability to compare alternative tropical farming systems accounting for soil depletion based upon the results of the present article.

[3] For example, Scott (1954) states that in the short run (within a single season), the fish population is one of the fixed inputs. More recent specifications include Clark (1976), Dasgupta and Heal (1979), and El Serafy (1991).

the control of any individual firm. That is, conventional inputs such as capital, labor, and energy are organized conditional upon expected resource stock abundance levels to generate the extractive flow. Increases (decreases) in resource abundance then shift the production technology, increasing (decreasing) the rate of extractive flow for any given input bundle. McFadden (1978) develops this approach within the framework of the firm's production possibilities set, treating environmental parameters (such as resource abundance) similar to disembodied technical change. Also, the resource stock places a maximum limit upon the extraction rate.

Resource abundance as a technology-shift parameter can be specified in the firm's neoclassical production function. This function, $F$, expresses the stock-flow relationship between the resource stock and the extractive activity at a given period. $F$ takes the vector of inputs, $X$, and applies it to the resource stock to extract flow $Y$, conditional upon the state of technical knowledge $t$ and resource stock abundance level $B$. It is written $Y = F(X \mid t, B)$.

An increase in the size of $B$ allows an increase in the flow rate of resource extraction for any given $X$ and $t$, so that $\delta F/\delta B > 0$. Similarly, technical progress shifts $F$, given $X$ and $t$, so that $\delta F/\delta t > 0$. Thus both the abundance of the resource stock and disembodied technological change may be treated as technology-shift parameters.[4]

Gordon (1954) treated fish abundance as a technological constraint in his seminal article on marine fisheries as common-property resource industries.[5] While this approach does not preclude managing the fishery as if the resource stock were an asset, the framework does properly specify the resource stock just like any other environmental parameter, as a technological constraint, instead of as an input under the control of individual firms.

Proper valuation of the common-property resource stock depends upon the specific property-right structure governing its use. Under competitive open-access conditions, the firm's utilization decision for the resource is not endogenous, and each firm ignores the effects of its production upon the resource stock. Each firm instead behaves as if the resource had a zero user cost, because the effect of a unit change in resource abundance on the open-access firm's profits is zero due to rent dissipation (Gordon, 1954; Smith, 1969; Capalbo, 1986). The firm's marginal costs and the market prices it faces include only the extraction component and not the user-cost component (the latter of which is zero).

In contrast, a sole owner must contend explicitly with the user cost, because the resource utilization decision is now endogenous through the choice of extraction rate and input usage (Capalbo, 1986; Smith, 1969). Social costs associated with the resource externality are now private costs to the firm and, along with extraction costs, factor into the firm's optimization problem (Smith, 1969). Market prices include the marginal user cost of the resource as a component of the full extraction cost. Similarly, the user cost is explicitly considered as a cost when property rights are not assigned but the emphasis is given to social evaluation of productivity growth.

## 3. The firm's optimization problem and productivity measures

■ Specification of the firm's profit maximization problem depends upon the nature of property or access rights (or aggregation level). I consider both sole-owner and open-access in situ common-property resources. Following standard practice (cf. Clark, 1976), I assume a Schaefer (1957)-type production technology, where each vessel's catch per unit of time is proportional to the resource stock and its costs are inversely proportional to the resource

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[4] Shifts in common-property resource abundance have the same effects upon isoquants for a neoclassical technology as exogenous technological change, since both are changes in technological constraints.

[5] Thus Gordon (1954, p. 136) states, "For each given level of population, a larger fishing effort will result in larger landings. Each population contour is, then, a production function for a given population level." As Gordon noted, this approach does not preclude the impact of catch increases on reducing the resource stock.

stock. I distinguish noncapital costs and inputs from capital to facilitate capital's role in a later discussion of capacity utilization (CU), but full static equilibrium in all inputs is initially allowed not to confound the discussion of property rights with that of CU. I give only the germane results here, with full development in Squires (1991).

The Lagrangian for the optimization problem of a sole owner (or society) is

$$\max_{Y_t, K_t, B_t} L = \{P_tY_t - G(Y_t, K_t, W_{jt}, B_t, t) - W_{Kt}K_t\} + \phi_1[B_t - Y_t] + \phi_2[B_{t+1} - B_t - h(B_t, Y_t, E_t, U_t)], \quad (1)$$

where $P_t$ is the product price, $W_{jt}$ is the price of the $j$th variable input $X_{jt}$, $W_{Kt}$ is the rental or services price of capital $K_t$, $t$ indexes the state of technical progress (assumed Hicks neutral and disembodied), $B_t$ is the resource stock, $h(\cdot)$ is the biological growth function, $Y_t$ is the current resource extraction rate, $G(Y_t, K_t, W_t, B_t, t)$ is the variable cost function for the optimal combination of variable inputs, where $\delta G/\delta B < 0$, and $\phi_i$ is the Lagrangian multiplier for constraint $i$.

The first constraint indicates that the extractive flow from the resource cannot exceed the resource stock itself.[6] The second represents discrete-time growth of the resource stock. Abundance in time $t$ is determined by its level in the previous period ($B_{t-1}$), its growth function ($h$), the resource extraction rate ($Y_t$), environmental parameters ($E_t$), and any public regulations ($U_t$). Not only are $Y_t$ and $K_t$ decision variables to the sole owner, $B_t$ is one as well via the choice of current extraction rate $Y_t$ and the long-run planning decision for $K_t$ (Capalbo, 1986; Smith, 1969). All *ex ante* expectations are assumed realized *ex post*.

The first-order conditions for an interior solution are

$$L_Y = P_t - G_Y - \phi_1 - \phi_2 h_Y = 0, \quad \text{or} \quad P_t - \phi_1 - \phi_2 h_Y = G_Y \quad (2a)$$

$$L_K = -W_K - G_K = 0, \quad \text{or} \quad W_K = -G_K \quad (2b)$$

$$L_{\phi 1} = B_t - Y_t = 0, \quad \text{or} \quad B_t = Y_t \quad (2c)$$

$$L_{\phi 2} = B_{t+1} - B_t - h(B_t, Y_t, E_t, U_t) = 0, \quad \text{or} \quad B_{t+1} - B_t = h(B_t, Y_t, E_t, U_t) \quad (2d)$$

$$L_B = -G_B + \phi_1 - \phi_2[1 + h_B] = 0, \quad \text{or} \quad -G_B = -\phi_1 + \phi_2[1 + h_B]. \quad (2e)$$

Condition (2a) states that the harvest rate should be selected such that marginal extraction cost $G_Y$ ($=\delta G/\delta Y$) equals product price less the marginal value of nonextinction $\phi_1$ less the marginal rent from additional fish recruits $\phi_2$ times the marginal impact of the current harvest rate on the resource stock $h_Y$ ($=\delta h/\delta Y$). Extinction is generally irrelevant, and $\phi_1$ may be set equal to zero.[7] Sole ownership implies $\phi_2 > 0$, so from (2a), $P_t = G_Y + \phi_2 h_Y$. Condition (2b) gives the reduction in variable costs, $-G_K = \delta G/\delta K$, from using one more unit of capital to produce a given output, or the shadow price of capital.

Condition (2e) demonstrates two benefits from a unit of resource in place at time $t$ (with $\phi_1 = 0$): (1) harvesting costs are lowered and (2) additional value accrues from future growth of the resource stock (Clark, 1976). These two benefits form the user cost, i.e., the opportunity cost to the user of taking a unit of the resource in the present period. Because the analysis is positive, concerned with measuring productivity growth, I do not consider the stationary-state equilibrium conditions for the stock in a normative analysis.

The continuous time Divisia index of total factor productivity using nonparametric growth accounting is

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[6] A referee noted that the inherent dynamic problem was reduced to its static equivalent. In particular, this first constraint suggests $B_t = Y_t$, although including this constraint really implies an equation of motion between the stock and flow instead of an equality. At any one period this distinction is unimportant.

[7] Extinction is usually unlikely unless biological growth rates are relatively low. When extinction is a real possibility, shadow prices can be measured by the methods of environmental valuation.

$$-\frac{\delta \ln C}{\delta t} = \frac{[P - \phi_2 h_Y]Y}{C}\frac{\dot{Y}}{Y} - \Sigma_j \frac{W_j X_j}{C}\frac{\dot{X}_j}{X_j} - \frac{W_K K}{C}\frac{\dot{K}}{K} - \frac{\phi_2[1 + h_B]B}{C}\frac{\dot{B}}{B}, \tag{3}$$

where $C = \Sigma_j W_j X_j + W_K K + \phi_2 h_Y Y + \phi_2[1 + h_B]B = PY$ with linear homogeneity, and the dots over variables represent time derivatives.

Equation (3) shows TFP measured as the residual after allocating the growth rate of output among changes in variable inputs, capital, and resource abundance, the latter specified as Hicks neutral and disembodied. The user cost of the marginal unit of the in situ resource, $\phi_2$, is explicitly considered in this sole-owner problem.

In the individual competitive firm's profit-maximization problem, $B_t$ is not a decision variable, so $h_B$ is not relevant, and each firm ignores $\phi_2$. Only indirectly through $h(B_t, Y_t, E_t, U_t)$ do changes in firms' resource extraction rates affect the resource stock level. The productivity measure is a special case of (3):[8]

$$-\frac{\delta \ln C}{\delta t} = \frac{\dot{Y}}{Y} - \Sigma_j \frac{W_j X_j}{C}\frac{\dot{X}_j}{X_j} - \frac{W_K K}{C}\frac{\dot{K}}{K} - \frac{\dot{B}}{B}, \tag{4}$$

where $C = \Sigma_j W_j X_j + W_K K = PY$ under constant returns to scale.

The productivity residual is biased without disentangling variations in $B_t$. In contrast to the sole-owner problem, because $B_t$ is not a decision variable to firms and $\phi_2 = 0$, proportional changes in abundance are simply pared away from the conventional productivity residual without weighting by cost shares in this positive analysis.

Regulation of a competitive open-access fishery can either develop property or access rights or impose production constraints. This section considers constraints on the extraction process for the competitive open-access fishery, since rights-based regulation is related to the sole-owner problem. Market failure remains because rights are underdeveloped, and the analysis remains firm-level and positive rather than normative.

Under a catch quota $Y^*$, the constraint $Y_t \leq Y^*$ is added to equations (1) and (2) (Denny, Fuss, and Waverman, 1981). The Lagrangian for a binding constraint, $\phi_Y$, is the virtual price of the quota (Rothbarth, 1940), and the unit quota rent is $P_t - \phi_Y$.[9] The first-order condition in the open-access problem is now $P_t - \phi_Y = G_Y$; vessels adjust catch rates until the unit quota rent equals marginal extraction cost. Alternatively, the cost of market failure can be imposed on firms by a landings tax $\Gamma$. (2a) is now $P_t = G_Y + \Gamma$; firms adjust the catch rate until price equals private marginal extraction cost plus tax.

With a binding regulation $K_t \leq K^*$, $\phi_K > 0$, production costs increase, and the net services price of capital becomes $W_K + \phi_K$.[10]

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[8] A referee noted that for large firms or small industries, the firm takes the behavior of a few rivals as given. This will yield a different rule than equation (4). Experience has shown that under small numbers, fishers often manage the fishery cooperatively, making the sole owner, equation (3), appropriate. Nonetheless, with the exception of highly specialized fisheries harvesting small localized stocks or distant-water fisheries harvesting on a world scale, the open access coupled with definite limitations on firm size creates competitive, atomistic industries, and (4) holds.

[9] Ultimately, reduced catch helps rebuild the resource stock, which enters the model through $G(\cdot)$ and the growth equation.

[10] $\phi_Y$ and $\phi_K$ could be estimated from a mathematical programming model as shadow prices when the constraints include limits on catch and capital, or as virtual prices from duality-based econometric models (see Squires, 1990). Also, production controls might seemingly preclude rent dissipation, implying $\phi_2 > 0$. However, production controls raise production costs (by inducing inefficiency), reduce rent, and do not alter the fundamental cause of rent dissipation, open access. Moreover, because the resource stock is still not a decision variable to individual open-access firms, even with production controls, firms continue to ignore user costs, and equation (4) remains appropriate for a positive, firm-level analysis (modified for $W_K + \phi_K$ and/or $P_t - \phi_Y$). Firms can respond to capital restrictions that limit the number of vessels by expanding the amount of capital on existing vessels. To the firm this is generally productive investment because it increases output, but to society it is usually unproductive (which can be incorporated following Conrad and Morrison, 1989).

Changes in the size of $B_t$ do not affect productivity measures as directly as indicated in equations (3) and (4). An input bundle often catches an increasing proportion of the residual resource stock as $B_t$ declines, due to the concentrating or schooling behavior of many fish species and the nature of the fishing technology (MacCall, 1990). As $B_t$ decreases in size, so does its spatial distribution, but the density of fish over an area or school size changes little. Fishing firms can quickly locate the remainder, even of a heavily depleted stock, and harvest at rates similar to those of a higher stock level.[11] Thus the "catchability" of stock is not directly related to $B_t$'s size and must be adjusted. Following standard procedures (MacCall, 1976), the catchability coefficient weighting $B_t$'s abundance is a power function (see below).[12]

Productivity measures are biased when output growth comes from changes in capacity utilization of quasi-fixed factors (CU) along with changes in variable factors and productivity (Berndt and Fuss, 1986) and common-property resource abundance. Altering the value and not the quantity of the quasi-fixed factors adjusts the productivity residual for variation in CU with growth accounting (Berndt and Fuss, 1986). Under constant returns to scale for the unregulated competitive open-access fishery,

$$P_tY_t = G(Y_t, K_t, W_t, B_t, t) + Z_{Kt}K_t = \Sigma_j W_{jt}X_{jt} + Z_{Kt}K_t.$$

Rearranging: $Z_{Kt} = [P_tY_t - G(\cdot)]/K_t = [P_tY_t - \Sigma_j W_{jt}X_{jt}]/K_t$. The quasi-rent $Z_{Kt}$ is the residual income not accruing to variable inputs per unit of capital stock (Hulten, 1986).[13]

## 4. The industry, data, and index construction

■ The Pacific coast trawl fishery comprises vessels in Washington, Oregon, and California harvesting a wide variety of groundfish and pelagic fish species and pink shrimp.[14] The three important trawl gear are groundfish (bottom or roller), shrimp, and midwater, the last used by vessels making at-sea deliveries of pelagic Pacific whiting in a joint venture with foreign fleets; production between gears is nonjoint. Vessels flow between the groundfish and shrimp trawl sectors with the rise and fall of shrimp abundance. Larger vessels may also fish in Alaskan waters.

Most vessels are unspecialized and diversified in the species caught. Vessels tend to be small, from 30 to 110 feet in length, to have crews of three for most vessels and seven for the joint venture vessels, and to land in one or more ports, and they may operate full or part time. Most fishing trips last from one to ten days. Few firms are horizontally integrated to multiple vessels. Vertical integration between shoreside processors and vessels also remains limited.

Revenue shares and catch indices by species are reported in Tables 1 and 2. Pink shrimp, Dover sole, rockfish, and Pacific whiting contribute the most revenue. Most species

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[11] When populations are cropped by harvesting, fish tend to redistribute themselves to best exploit the most favorable habitats. In turn, this tends to maintain the density of their population centered around the areas of favorable habitat, but their total area of distribution contracts from more marginal habitats. Hence, vessels tend to harvest the most favorable locations, maintaining catchability at relatively stable levels, even if populations are declining (MacCall, 1990).

[12] I am grateful to Alec MacCall for raising this issue and suggesting catchability coefficients. In addition, the Schaefer model assumes a uniform distribution of the fish population. As Clark (1976) notes, however, the Schaefer cost function is still suitable when fish concentrations are uneven or when fish school, if it is understood that the units of the resource stock are considered standard school biomass.

[13] An anonymous referee noted that $Z_K$ could also include the effects of changing economies of scale if constant returns to scale do not hold. It could also include other returns, such as the existence of market power, should these pertain. Tobin's $q$ can be used with multiple quasi-fixed inputs (Berndt and Fuss, 1986).

[14] Trawlers drag a net from the stern of a vessel, haul it in, dump and sort the contents of the catch on the deck, and store it in holds below. Groundfish are demersal fish, i.e., they live on or near the bottom and are not fundamentally migratory. Pelagic fish are migratory and live higher in the water column.

**TABLE 1** **Revenue Shares**

| Year | Dover Sole | Other Flatfish | Rockfish | Sablefish | Miscellaneous Groundfish | Pink Shrimp | Pacific Whiting |
|---|---|---|---|---|---|---|---|
| 1981 | 0.114 | 0.095 | 0.258 | 0.026 | 0.136 | 0.284 | 0.088 |
| 1982 | 0.131 | 0.109 | 0.262 | 0.043 | 0.156 | 0.174 | 0.125 |
| 1983 | 0.138 | 0.109 | 0.254 | 0.037 | 0.179 | 0.137 | 0.145 |
| 1984 | 0.146 | 0.099 | 0.240 | 0.044 | 0.222 | 0.067 | 0.182 |
| 1985 | 0.198 | 0.140 | 0.311 | 0.063 | 0.053 | 0.164 | 0.069 |
| 1986 | 0.125 | 0.088 | 0.229 | 0.049 | 0.021 | 0.371 | 0.118 |
| 1987 | 0.097 | 0.082 | 0.201 | 0.041 | 0.036 | 0.432 | 0.110 |
| 1988 | 0.115 | 0.081 | 0.227 | 0.044 | 0.054 | 0.317 | 0.162 |
| 1989 | 0.107 | 0.094 | 0.237 | 0.041 | 0.048 | 0.265 | 0.208 |

Source: PacFIN Management Data Base.

**TABLE 2** **Percentage Annual Output Growth Rates**

| Year | Dover Sole | Petrale Sole | Other Flatfish | Rockfish |
|---|---|---|---|---|
| 1982 | 2.97 | 0.93 | 1.37 | 0.37 |
| 1983 | −0.75 | −0.79 | −1.32 | −8.44 |
| 1984 | −0.83 | −1.04 | −0.60 | −6.32 |
| 1985 | 1.70 | 0.34 | 1.34 | −0.03 |
| 1986 | 3.79 | −0.70 | −1.77 | −3.06 |
| 1987 | −0.75 | 0.87 | 0.89 | −8.78 |
| 1988 | 0.23 | −0.18 | −1.09 | 11.41 |
| 1989 | 1.02 | 0.02 | 1.66 | 2.14 |
| Mean | −0.02 | −0.07 | 0.06 | −1.59 |

| Year | Pacific Whiting Groundfish Trawl | Miscellaneous Groundfish | Pink Shrimp | Pacific Whiting Joint Venture |
|---|---|---|---|---|
| 1982 | 0.05 | 4.96 | −7.72 | 4.66 |
| 1983 | 0.01 | 0.89 | −11.56 | 0.90 |
| 1984 | 0.43 | 1.53 | −3.23 | 1.47 |
| 1985 | 0.30 | −49.72 | 11.31 | −11.44 |
| 1986 | −0.11 | −0.10 | 20.28 | 8.86 |
| 1987 | 0.20 | 0.68 | 8.72 | 2.99 |
| 1988 | 0.05 | −0.87 | 1.51 | 3.35 |
| 1989 | 0.29 | −0.94 | 2.74 | 7.52 |
| Mean | 0.15 | −5.44 | 2.75 | 2.29 |

| Year | Sablefish | Pacific Cod and Lingcod | Aggregate Output |
|---|---|---|---|
| 1982 | 2.12 | 0.01 | 0.59 |
| 1983 | −1.39 | −0.13 | −3.75 |
| 1984 | 0.41 | −0.12 | 1.37 |
| 1985 | −0.51 | 1.84 | 1.44 |
| 1986 | −0.98 | −3.61 | 7.18 |
| 1987 | −0.04 | 0.06 | 2.34 |
| 1988 | −0.83 | 3.54 | 3.66 |
| 1989 | 0.15 | −1.13 | 2.98 |
| Mean | −0.13 | 0.06 | 1.63 |

**TABLE 3** **Percentage Annual Growth Rates of Biomasses**

| | Species: No Catchability Correction | | | | | Aggregate | | |
|---|---|---|---|---|---|---|---|---|
| Year | Flatfish | Rockfish | Sablefish | Whiting | Shrimp | (1) | (2) | (3) |
| 1982 | −1.05 | −9.90 | −0.07 | 7.15 | −10.42 | −5.84 | −2.92 | −4.78 |
| 1983 | 2.29 | −13.42 | −0.24 | −1.20 | −15.59 | −14.41 | −7.21 | −8.91 |
| 1984 | −4.13 | −10.97 | −0.33 | −0.59 | −4.31 | −9.75 | −4.88 | −6.87 |
| 1985 | −1.00 | −5.92 | −0.49 | −0.65 | 15.98 | 7.68 | 3.84 | 5.65 |
| 1986 | −0.98 | −4.05 | −0.63 | 4.75 | 27.27 | 22.52 | 11.26 | 15.02 |
| 1987 | −0.19 | −5.58 | −0.41 | −1.37 | 11.09 | 6.17 | 3.09 | 4.70 |
| 1988 | −0.52 | −9.84 | −0.18 | −2.86 | 1.91 | −3.51 | −1.75 | −1.67 |
| 1989 | −0.66 | −1.60 | −0.23 | −3.44 | 3.56 | −0.97 | −0.48 | −0.22 |
| Mean | −0.78 | −7.66 | −0.32 | 0.22 | 3.69 | 0.24 | 0.12 | 0.37 |

Notes: (1) No catchability correction for aggregate biomass index.
(2) Uniform square root catchability correction.
(3) Differential power catchability correction (see text).

were relatively unexploited at the start of the decade but were subsequently harvested at unsustainable rates, causing declining biomass (Table 3).

☐ **Data.** The analysis covers 1981–1989, the only years with comprehensive economic and biological data. Squires (1988) gives details for all data and index construction except the biological, which is reported in Squires (1991). Electronic spreadsheets with all calculations and data or summary tables of the raw data are available from the author upon request. The output indices require pounds landed and revenues by U.S. vessels at ports in Washington, Oregon, and California by species. Revenue and landings data are from the PacFIN Management Data Base (PacFIN) of the National Marine Fisheries Service (NMFS). All values are deflated by the GNP implicit deflator.

By 1989, sablefish production faced a consistently binding quota. Hence 1989 sablefish output was valued by $P - \phi_Y$, its implicit unit rent, where $\phi_Y$ was its virtual price. Coastwide estimates of $\phi_Y$ were unavailable, but based on a study of a Northern California trawl fishery (Squires, 1990), $\phi_Y$ was set at 68% of the product price.

Three major inputs are distinguished: labor, capital, and energy. The labor indices are bilateral Tornqvist chain indices for each region for three labor categories: crew, engineer, and captain. Each regional index is aggregated to a fleet index weighting by regional labor-cost shares. This two-step procedure with a superlative chain index gives approximate consistency in aggregation (Diewert, 1978) and captures more accurately coastwide variation in costs and input usage. Each labor category is valued at its opportunity cost for the region's representative home port. The opportunity cost for crew, taken from *County Business Patterns* (U.S. Bureau of the Census), equals the average wage in the retail, transportation, and manufacturing sectors. Engineers' opportunity wage, taken from state reports and from the *Area Wage Surveys* (Bureau of Labor Statistics), equals that of journeyman auto mechanics. The opportunity cost of captains is 20% more than that of crewmembers. The flow of labor services is the number in each labor category multiplied by the number of annual landings from PacFIN.[15]

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[15] Virtually all trawl vessels use a crew of three. Hence, one person from each labor category is specified. The representative home port of Washington is Westport; of Oregon, Newport; of Northern California, Crescent City; and of Central California, Moss Landing.

**TABLE 4** **Input Cost Shares**

| | Pacific Trawl Fleet | | | | | | Groundfish Trawlers | | |
|---|---|---|---|---|---|---|---|---|---|
| | Capital Services Price | | | Quasi-Rent to Capital | | | Quasi-Rent to Capital | | |
| Year | Labor | Fuel | Capital | Labor | Fuel | Capital | Labor | Fuel | Capital |
| 1981 | 0.418 | 0.180 | 0.402 | 0.363 | 0.156 | 0.481 | 0.544 | 0.163 | 0.292 |
| 1982 | 0.421 | 0.175 | 0.404 | 0.364 | 0.152 | 0.484 | 0.506 | 0.169 | 0.325 |
| 1983 | 0.453 | 0.157 | 0.390 | 0.454 | 0.158 | 0.388 | 0.610 | 0.189 | 0.201 |
| 1984 | 0.500 | 0.137 | 0.403 | 0.468 | 0.140 | 0.392 | 0.547 | 0.168 | 0.285 |
| 1985 | 0.459 | 0.156 | 0.386 | 0.510 | 0.173 | 0.317 | 0.588 | 0.198 | 0.214 |
| 1986 | 0.523 | 0.088 | 0.389 | 0.395 | 0.066 | 0.539 | 0.581 | 0.082 | 0.337 |
| 1987 | 0.478 | 0.098 | 0.424 | 0.306 | 0.071 | 0.628 | 0.477 | 0.086 | 0.437 |
| 1988 | 0.479 | 0.090 | 0.431 | 0.402 | 0.076 | 0.522 | 0.563 | 0.095 | 0.342 |
| 1989 | 0.484 | 0.098 | 0.418 | 0.349 | 0.070 | 0.581 | 0.485 | 0.086 | 0.428 |

Source: See text.
Note: Pacific trawl fleet includes groundfish, shrimp, and midwater joint venture trawl vessels.

The energy index is calculated by an economic-engineering approach. Annual fuel consumption is derived by dividing the annual fuel expenses of a sample of vessels by port-specific diesel fuel prices. Dividing each vessel's annual fuel consumption by its annual landings and averaging over the region's vessels gives the region's mean implicit fuel consumption per landing.[16] Each region's total annual fuel consumption is the product of its mean fuel-consumption rate and number of annual landings. Fuel-expense data come from federal income tax returns, and fuel prices come from quarterly telephone surveys (monthly in later years) of 32 marine fuel docks coastwide for the cash price of 600 gallons of No. 2 marine diesel fuel.

The capital index is a bilateral Tornqvist chain index for the number of vessels in each region for three length classes: (1) 49 feet or less, (2) 50–74 feet, (3) 75 feet and over. Each regional index is aggregated to a fleet index using regional capital cost shares as weights. Vessel counts are from states. The price of capital services, $P_K$, reflects (1) acquisition cost, from federal income tax returns for vessels built or purchased after the Magnuson Fishery Conservation and Management Act (MFCMA); (2) the interest rate of Moody's seasoned issues for corporate bonds rated Baa (capturing fishing's high risk): and (3) a 7% depreciation rate used by NMFS. Table 4 reports input cost shares.

☐ **Resource stock.** The catchability-weighted measure of $B_{it}$ is $B_{it}^{c_{it}}$, where $B_{it}$ is the biomass of species $i$ in time $t$ and $c_{it}$ is its catchability coefficient. The aggregate biomass index is $B_t = \Sigma_i R_{it} B_{it}^{c_{it}}$, where $R_{it}$ is the revenue share of species $i$ in time $t$. Recommended estimates of $c_{it}$ were as follows: flatfish 0.9, rockfish 0.5, sablefish 0.7, Pacific whiting 0.5, and pink shrimp 0.7; the more a species schools, the smaller is $c_{it}$.

Revenue shares are from PacFin (Table 1). Biomass estimates for the ten species are from Pacific Fishery Management Council (1990) or by personal communication with the author. These estimates were derived mostly from population models, usually the stock synthesis model (Methot, 1990) or, occasionally, cohort analysis (cf. Clark, 1976).[17] Trawl

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[16] The fuel consumption rates per vessel in gallons per trip by region are (1) Washington, 910.64, (2) Oregon, 657.17, and (3) California, 557.92. The rates reflect the increasing width of the continental shelf and hence increasing trip length from California to Washington.

[17] The stock synthesis model is a large age-structured simulation model where 33 parameters are estimated by maximizing a composite likelihood function based on fishery and fishery-independent data. Cohort analysis uses age-structured models.

surveys of abundance were used in a few instances. Because of the uncertainty with biomass assessments, some degree of uncertainty is introduced into the biomass index. Species without biomass estimates were assumed to change at the same rate as related species.

Pink shrimp biomass is related to environmental parameters rather than the size of resource stock.[18] Hence, biomass is unstable and difficult to estimate, and estimates instead followed a recommended "rule of thumb": 130% of total harvest. All flatfish (flounders, soles) were assumed to change at the same rate as Dover sole (the only flatfish with complete biomass estimates). The aggregate rockfish index comprised widow rockfish, Pacific ocean perch, bocaccio, chilipepper, yellowtail, canary, and thornyheads. It was constructed in two stages to incorporate qualitative information when quantitative information was unavailable and to allow for wide diversity of behavior and habitat.

□ **Tornqvist productivity index.** A discrete-time approximation to the continuous Divisia index of (4) is given by the Tornqvist approximation. This index for an unregulated open-access fishery allowing for variations in CU and resource abundance becomes

$$\ln(\mathrm{TFP}_t/\mathrm{TFP}_{t-1}) = 0.5\Sigma_i(R_{it} + R_{i,t-1})\ln(Y_{it}/Y_{i,t-1}) - 0.5\Sigma_j(S_{jt} + S_{j,t-1}) \times \ln(X_{jt}/X_{j,t-1}) - 0.5(S_{Kt} + S_{K,t-1})\ln(K_t/K_{t-1}) - \ln(B_t/B_{t-1}), \quad (5)$$

where $B$ is the composite index of resource abundance, $R_i = (P_i Y_i)/(\Sigma_i P_i Y_i)$ is the revenue share for output $i$, $S_j = (W_j X_j)/(\Sigma_i P_i Y_i)$ is the cost share for variable input $X_j$, and $S_K = (Z_K K)/(\Sigma_i P_i Y_i)$ is the capital cost share allowing for variations in CU.

## 5. Empirical results

■ The empirical results for the open-access Pacific coast trawl fishery demonstrate the importance of adjusting the multifactor productivity residual for variations in (1) capacity utilization, (2) resource abundance, and (3) the catchability coefficient. Failure to make these adjustments biases productivity measures.

Biomass growth (Table 3) indicates generally declining Pacific whiting biomass, punctured by occasional increases, reflecting young age at maturity and the sporadic recruitment of strong year classes of juvenile fish into the fishable stock. The unstable pink shrimp biomass reflects the unstable growth rate due to fluctuations in environmental parameters. The overall biomass index is strongly influenced by whiting and pink shrimp due to their large, fluctuating biomasses and revenue shares.

The rockfish, flatfish, and sablefish growth rates (Table 3) reflect the steady, prolonged decline in biomass due to unsustainable catch rates (Table 2) greater than the slow net growth of the biomass (this reflects long lives, slow growth, and steady recruitment rates).

The late 1970s and early 1980s were generally years with $\mathrm{CU} > 1$ (Table 5). Production expanded moderately (Table 2) because the domestic fleet no longer faced foreign competition following the MFCMA of 1977 (which restricted foreign fishing and created exclusive fishery zones out to 200 miles) and because several resource stocks (particularly rockfish) were harvested at rates exceeding maximum sustainable yield (MSY). New vessels were constructed, increasing fleet size and aggregate input use (Table 6). Around late 1982, pink shrimp virtually disappeared because of El Niño (which substantially altered ocean temperature), and output and input prices declined (Table 7). The quasi-rent to capital was less than the capital services price, i.e., $Z_K < W_K$, and $\mathrm{CU} < 1$ (Table 5). Bankruptcies

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[18] Shrimp abundance fluctuates unpredictably from year to year. Because shrimp are short-lived (3–4 years), a very strong or weak year class can change greatly the total biomass (year classes differ by as much as tenfold). Spawning depends primarily upon environmental parameters rather than the existing spawning stock, i.e., there is not a clearly defined relationship between female spawning biomass and recruitment.

**TABLE 5** **Capital Prices and Capacity Utilization per Vessel in the Pacific Coast Trawl Fishery, 1981–1989**

| Year | Capital Services Price ($W_K$) | Quasi-Rent to Capital ($Z_K$) | Capacity Utilization |
|---|---|---|---|
| 1981 | 60,535 | 79,487 | $CU > 1$ |
| 1982 | 62,859 | 84,067 | $CU > 1$ |
| 1983 | 55,405 | 53,041 | $CU < 1$ |
| 1984 | 56,082 | 51,096 | $CU < 1$ |
| 1985 | 53,501 | 38,002 | $CU < 1$ |
| 1986 | 47,628 | 82,228 | $CU > 1$ |
| 1987 | 56,728 | 116,133 | $CU > 1$ |
| 1988 | 57,535 | 77,486 | $CU > 1$ |
| 1989 | 55,437 | 96,756 | $CU > 1$ |

Note: 1981 dollars. Mean per-vessel values.

increased, and a number of vessels went idle or left the fleet (Table 6), transferring activities to Alaska, or were sunk or burnt; disinvestment occurred with a lag.

Around 1985–1986, overall biomass began to rebuild, primarily from a dramatic resurgence of the high-priced pink shrimp (as El Niño subsided) and a growth in Pacific whiting biomass (Table 3). Real fuel prices and interest rates also dropped, while real output prices for most species rose, except for a dip in 1988 (Table 7). Hence, $Z_K > W_K$ and CU $> 1$, signalling investment incentives (Table 5). Fleet size and aggregate input (Table 6) responded: it expanded, albeit only with a lag, and jumped by 6.3% in 1987.

In 1988–1989, the overall biomass declined slightly due to a plunge in rockfish abundance beginning in 1987 and a decline in Pacific whiting (Table 3), and output prices dropped in 1988 but climbed in 1989 (Table 7). $Z_K$ fell by 36% but remained above $W_K$, CU remained above one, and the fleet size remained stable.

In sum, CU signalled private investment incentives for most of the decade, but the fishery was overcapitalized from a social perspective due to the open-access externality, and harvesting rates were often greater than MSY. By the decade's end, most resources had fallen to near or below MSY levels with stable or declining trends.

Table 8 reports total factor productivity measures. There are no adjustments for changes in resource abundance in columns 1 or 2. Column 1 measures productivity assuming full equilibrium of capital. The combined effect of technical progress and resource abundance

**TABLE 6** ***Aggregate Input Growth Rates***

| Year | Washington | Oregon | Northern California | Central California | Fleet Aggregate |
|---|---|---|---|---|---|
| 1982 | −10.30 | 2.53 | 20.52 | 3.27 | 7.12 |
| 1983 | 4.25 | 3.38 | −11.15 | −10.93 | 0.14 |
| 1984 | −9.40 | −7.48 | −2.49 | −9.11 | −7.24 |
| 1985 | −2.45 | −6.87 | 5.90 | 19.81 | 0.67 |
| 1986 | 4.93 | 1.91 | −14.76 | −34.99 | −2.75 |
| 1987 | 5.70 | 9.50 | 5.21 | −28.40 | 6.33 |
| 1988 | 6.91 | −7.55 | −3.96 | −8.41 | −4.00 |
| 1989 | −2.61 | 8.85 | 0.02 | −0.40 | 4.65 |
| Mean | −0.37 | 0.53 | −0.09 | −4.96 | 0.61 |

Note: Tornqvist bilateral chain index. Percentage growth rate. Full static equilibrium of capital not imposed. Capital valued by quasi-rent rather than capital services price.

**TABLE 7** **Implicit Aggregate Output and Input Price Indices**

| Year | Output | Input |
|---|---|---|
| 1981 | 1.000 | 1.000 |
| 1982 | 1.042 | 1.003 |
| 1983 | 0.839 | 0.876 |
| 1984 | 0.886 | 0.940 |
| 1985 | 0.957 | 0.926 |
| 1986 | 1.201 | 1.030 |
| 1987 | 1.385 | 1.020 |
| 1988 | 0.662 | 1.016 |
| 1989 | 1.199 | 0.938 |

Note: Formed by Fisher's factor-reversal test.

changes in column 1 indicates two cycles of declines followed by increases in productivity. Column 2, which adjusts for CU variations, shows reduced productivity growth, dampened fluctuations in growth rates, and a more complex pattern.

Excluding resource growth will bias productivity measures. Column 3 of Table 8 reports TFP incorporating variations in CU and biomass but not catchability. In years of declining biomass, such as 1981–1984 and 1988–1989, TFP is otherwise understated. Similarly, when biomass increases, such as during 1985–1987, the greater ease of finding and catching fish, unless accounted for in this stock-flow production technology, overstates TFP growth. Annual productivity growth can also reverse signs unless resource growth is included.

Adjusting the biomass estimates for variations in catchability in column 4 of Table 8 generally dampens the effects of changes in resource abundance upon productivity growth and its year-to-year fluctuations. This enhanced stability follows from the density-dependent habitat selection of fish, as discussed above. Mean productivity growth is about half after the full set of corrections.

Productivity growth over the decade averaged a disappointing 0.65%. The productivity growth rate over 1981–1984, years of declining biomass in all species, averaged a strong 5.33%. Growth averaged −2.15% over 1985–1989, years of rising overall biomass (or modest declines but nonetheless falling for all species except shrimp).

**TABLE 8** **Total Factor Productivity Growth in the Pacific Coast Trawl Fishery, 1981–1989**

| Year | No Correction[a] (1) | Capacity Utilization Correction[b] (2) | Capacity Utilization and Biomass Correction[c] (3) | Full Correction[d] (4) |
|---|---|---|---|---|
| 1982 | −8.139 | −6.538 | −0.700 | −1.755 |
| 1983 | −5.028 | −3.889 | 10.526 | 5.017 |
| 1984 | 9.623 | 5.871 | 15.622 | 12.737 |
| 1985 | 2.967 | 7.763 | −6.902 | −4.873 |
| 1986 | 14.163 | 9.928 | −12.589 | −5.089 |
| 1987 | −8.916 | −3.988 | −10.161 | −8.689 |
| 1988 | 2.255 | 7.662 | 11.171 | 9.332 |
| 1989 | 1.653 | −1.664 | −0.697 | −1.444 |
| Mean | 1.072 | 1.020 | 0.783 | 0.654 |

[a] Long-run equilibrium in capital and no biomass correction.
[b] Correction for variation in capacity utilization but not biomass.
[c] Correction for variation in capacity utilization and biomass but not for variation in catchability coefficient.
[d] Correction for variation in capacity utilization and biomass, and variability in catchability coefficient.
Note: Calculated by Tornqvist bilateral chain indices. Percentage annual growth rate.

**TABLE 9** **Total Factor Productivity Growth for Groundfish Trawl Only**

| Year | Multifactor Productivity | Aggregate Output | Aggregate Input | Aggregate Biomass | Capacity Utilization |
|---|---|---|---|---|---|
| 1982 | −10.64 | 2.88 | 15.90 | −2.39 | <1 |
| 1983 | −11.24 | −4.51 | 7.07 | −3.36 | <1 |
| 1984 | 11.71 | −2.57 | −8.05 | −6.23 | <1 |
| 1985 | 3.18 | 0.64 | −0.37 | −2.17 | >1 |
| 1986 | 28.79 | −4.25 | −31.08 | −1.96 | <1 |
| 1987 | −12.23 | −7.95 | 6.35 | −2.07 | >1 |
| 1988 | 10.40 | 10.35 | 3.26 | −3.31 | <1 |
| 1989 | 2.37 | 2.50 | 1.78 | −1.65 | >1 |
| Mean: | 2.79 | −0.36 | −0.64 | −2.52 | |

Note: Differential power catchability correction (see text). Pink shrimp and joint venture midwater trawl vessels excluded. Correction for variation in capacity utilization (see text). Tornqvist bilateral chain indices and percentage annual growth rates.

Productivity in this stock-flow technology ostensibly rose when overall output growth was unsustainable but fell under sustainable harvesting rates. More accurately, however, exploitation rates for most species except shrimp were unsustainable in most years. Growth in productivity and overall biomass were instead driven by, and inversely related to, the large rises and falls in shrimp biomass (responding to environmental conditions) and, to a lesser extent, whiting biomass (due to young age at maturity and sporadic recruitment of large year classes). High revenue shares gave emphasis. Yet their biomass growth and variation, particularly for shrimp, depend largely upon biological and environmental processes beyond the control of regulators or industry. Firms suffer low apparent productivity growth because of the substantial biological noise and the corresponding difficulty in organizing efficient harvesting.[19]

To assess productivity growth without the swamping effect from the whiting and shrimp biomasses, all indices were recalculated for groundfish vessels only, the heart of the Pacific trawl fleet. Shrimp biomass was excluded entirely, while whiting biomass was included but weighted by a revenue share excluding joint venture trawlers (groundfish trawlers catch some whiting). Table 9 reports the chain indices and growth rates for productivity, aggregate output and input, and biomass. Productivity growth averaged 2.79%, and the annual variation declined considerably as the biological noise (from pink shrimp and joint venture-caught whiting) was removed from the system. Productivity growth also became consistently positive from mid-decade, except in 1987, when CU and aggregate input surged. These changes followed from the transfer of exiting vessels to Alaska and the resurging shrimp biomass, both of which attracted vessels out of groundfishing. The rate of groundfish biomass decline slowed as well (Table 9). Productivity also grew in response to extensive technical progress (discussed below), even in the face of excessive input use under open access.

The productivity growth rate in both the entire fleet and groundfish-only trawlers displayed considerable annual variation. The ability of mobile vessels to rapidly enter and exit an open-access fishery and switch gear, coupled with fluctuations in resource abundance, generated sharp productivity swings.

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[19] Pink shrimp are located in discrete, known beds. However, when vessels repeatedly tow through the area, shrimp progressively disperse and become increasingly hard to find. Shrimp may remain in the general area but do not congregate. Hence, there is much searching, even though discrete grounds are known, and dragging over beds imposes costs that build up over time. Shrimp also respond to variations in light, so shrimp concentrations can vary daily. (Jim Wilen, personal communication.) In short, a good catch one day can be followed by a bad catch the next day, which when coupled with the wide annual variations of biomass, creates substantial inefficiencies.

Future productivity growth rates in the entire fleet may slow and smoothen. Alaska now increasingly offers low returns, so vessels will remain in the overcapitalized Pacific coast fishery, further retarding productivity growth. This was exacerbated when the resurging biomass of high-priced shrimp drew many vessels into the overall fleet.[20] Lower interest rates also lessened pressures from vessel mortgages, retaining vessels.

Higher productivity growth may be enjoyed under access control. Without reduced inputs from a vigorous limited-access program, future productivity growth could even fall as vessels face comprehensive catch quotas, as search times for locating new grounds increase, and as transit times to marginal grounds lengthen.

The most important sources of technical progress were electronics and the application of scientific rather than craft principles to vessel and equipment design and to harvesting methods.[21] Fishing is a semisystematic hunting process for an unseen quarry. Formerly, to locate fish, fishermen had to rely primarily on the experience painstakingly built up over a lifetime. Fishing was also more hampered by inclement weather and seas. However, recent advancements make it harder for fish to hide from their captors, and they also allow higher catch rates, longer seasons, and new fishing grounds.

The rapid introduction of electronic navigation aids (e.g., Loran C and track plotters) and fish finders (chromoscopes and sonar to examine the bottom) dramatically raised the ability to find fish, even by species. Search time decreased as captains returned easily to precise locations of past success or found fish in new locations. The ability to assess the type of bottom (rock, mud, gravel, etc.) allowed more precise net placement, choice of the appropriate net type (e.g., for rocky or muddy bottoms), and selection of the type of fish to harvest (different fish prefer different habitats). Moreover, echo sounders distinguish differences in the air bladders of fish, giving greater control over location, size of fish school, and type of fish to harvest. The quality of electronics has improved substantially and unit costs have fallen rapidly, allowing extensive diffusion.

Gear advances also took place. Nets widened, allowing a greater volume of water to be swept and more fish caught per hour towed. Previously, most rockfish were caught with gear designed for harvesting flatfish. Winches of higher speed and greater capacity allowed larger nets to be released and retrieved at faster rates.

There have also been advances in boat and engine design. Vessels got longer and replaced steel or fiberglass with wood. Marine architects tested models of their designs in computer simulations and in flume tanks. Designs cut down hull drag and gave maximum efficiency. A cort nozzle gave engines greater thrust, allowing greater fuel economy for net towing and transit.

License limitation programs, which limit the number of vessels, are plagued by the continued increase in productivity and consequent pressures on the resource, even though vessel numbers have been capped. Programs to remove vessels dampen harvesting pressures, but continued productivity growth of the remaining vessels creates countervailing pressures. A recent license limitation program for groundfish vessels could be hampered by productivity

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[20] Most of the increase in vessel numbers and fishing trips occurred off Washington and Oregon, the predominant shrimping area. From 1985 to 1989, exclusive shrimp vessels increased in Washington from 12 to 38 and in Oregon from 25 to 69. Some otter trawl vessels exited in 1988, after dramatic surges in shrimp biomass from 1984 through 1988 and a general output price collapse (Table 7), but vessel numbers nonetheless remained at historically high levels in these two states.

[21] In a narrow sense, much of the recent technical progress is embodied technical change, so that vintage effects may theoretically be important. However—because the investment value is relatively small and much of this technical change is related to the managerial function, information, and learning by doing—representing technical change as Hicks neutral and disembodied without vintage effects is satisfactory. See Burnett (1991), Dewees and Hawkes (1988), Crowley (1991), and Squires (1991) for additional discussion on recent technological advancements in the fishery.

growth without compensating vessel reductions, or by eligible shrimp vessels reentering the groundfish sector.

## 6. Concluding remarks

■ Proper treatment of the resource stock in common-property resource industries is important for measures of productivity or technical progress and, more generally, for technology specification and accurate policymaking. The empirical analysis demonstrated that disentangling the productivity residual from changes in the resource's abundance and catchability and variations in capacity utilization honed the productivity residual to finer precision, lowering the mean growth rate by about half. Biological noise from highly variable, often short-lived resources can affect efficiency and productivity measures.

Unsustainable exploitation rates cropped the biomass of most species from lightly harvested levels to near or below maximum sustainable yield levels by 1989. Overcapitalization, tighter catch quotas, and declining catch rates from excessive inputs under open access may dampen future productivity growth, even in the face of extensive technical progress, unless vessel numbers are reduced by a vessel purchase program or a system of individual transferable quotas.

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