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Productivity Growth in Natural Resource Industries and the Environment:  
An Application to the Korean Tuna Purse-Seine Fleet in the Pacific Ocean

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Productivity Growth in Natural Resource Industries and the Environment:  
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**Abstract:** Measures of multifactor productivity growth in natural resource industries are biased without accounting for the effects on the environment. This paper introduces environmental effects into an output-oriented Malmquist index of multifactor productivity growth to evaluate growth in productivity, technology, and technical efficiency for Korean purse seine vessels fishing for tuna in the Western and Central Pacific Ocean.

**Key Words:** Productivity, technical change, environment, natural resources, Malmquist index, Pacific tuna fisheries, Korea

**JEL Codes:** D24, O3, Q2

## **1. Introduction**

An important issue for accurate measurement of multifactor productivity (MFP) growth in many industries is accounting for changes in the state of the environment. Environmental effects are particularly important in industries directly utilizing the environment and natural resources such as agriculture, mining, forestry, fisheries, or power generation. These changes in the state of the environment are unpriced, which require treatment in MFP measures that are different from priced inputs and outputs. Environmental changes can include, for example, precipitation, temperature, short-term (El Niño-Southern Oscillation events), medium-term (decadal-scale events), and long-term climate change.

The environmental, resource, and productivity literature have devoted some attention to environmental effects in productivity and economic growth, but formal treatments in models of productivity growth and technical change either overlook environmental effects or these ideas are not fully developed. Bleischwitz (2001) provided a broad historical overview of the general subject of natural resources, the environment, and productivity growth. Grubler, Nakicenovic, and Nordhaus (2002) considered productivity growth, technical change and the environment in general. Jaffee, Newell, and Stavins (2002) discussed environmental policy and technical change, although a formal treatment of productivity growth, including the impact of environmental factors, was not fully developed. The chapters in Simpson (1999) can be extended to explicitly include natural resource stocks and environmental factors. Squires and Reid (2001, 2002, 2003, 2004) estimated Malmquist indices of MFP growth for vessels of the different distant water and coastal flag states in the tuna purse seine fishery of the Western and

Central Pacific Ocean (WCPO), accounting for changes in resource stocks and the state of the environment, but did not develop a formal treatment. Felthoven and Paul (2004) briefly surveyed environmental variables in MFP measures for fisheries. Arrow *et al.* (in press) broadly discussed the environment and resource stocks in productivity growth and adjusted the Solow (1957) productivity residual for changes in natural resource stocks. In population dynamics literature, Freon (1988) allowed environmental variation in the environmental carrying capacity and catchability coefficient of surplus production models, both of which are otherwise constants.

Measures of productivity growth in natural resource industries are biased without accounting for changes in resource stocks and the state of the environment. Disentangling productivity growth from changes in resource stocks was addressed by Lasserre and Ouellette (1988, 1991) for non-renewable resources and Squires (1988, 1992) for renewable resources. Murray (2004) developed a theoretical model of technical change in natural resource industries. McConnell and Strand (1989) indicated that the change in biomass overtime is positively related to the predetermined vectors of variables representing water quality, implying that improvements in water quality should increase the growth in biomass.

The process of productivity growth and technical progress in industries exploiting common resources, such as marine fisheries, can differ from that in some other natural resource industries where productivity growth and technical progress are viewed as enhancing the resource stock. For example, in the former-mentioned common resources such as fisheries, productivity growth and technical progress simply increase the rate of exploitation. For example, the costs of producing forest resources today are no longer

limited to the costs of extraction but increasingly include planting, growing and harvesting costs (Sedjo 1999). In this regard, economic and productivity growth in the forest sector are edging closer to agriculture and moving away from an industry that exploits natural resources as they are found in nature, i.e. as forestry moves from exploiting resources at the extensive margin to the intensive margin.

This paper formally and empirically incorporates unpriced environmental effects into measures of MFP growth by introducing sea surface temperature into the stock-flow production technology for a renewable common resource, marine fish.<sup>1</sup> Specifically, this paper develops output-oriented Malmquist indices of multifactor productivity, technical change, and technical efficiency while accounting for changes in resource stock abundance and the state of the environment. We specify the state of the unpriced environment as a technological constraint beyond the control of the individual firm, in a similar vein to the resource stock (Squires 1992), so that, following Gordon (1954) and McFadden (1978), it becomes a technology shift variable.<sup>2</sup> We evaluate productivity in a framework developed from the neoclassical theory of the firm when there is a stock-flow production technology with a common natural resource.<sup>3</sup> The paper demonstrates that the output-oriented Malmquist index approach, which does not necessarily require cost, revenue, or price data, is especially well suited to incorporate unpriced measures of resource stocks and states of the environment such as climate and ecosystem services.

We evaluate productivity growth for a micro-level panel of Korean tropical tuna purse seine vessels (essentially at the plant level) harvesting common-pool yellowfin (*Thunnus albacares*), skipjack (*Katsuwonus pelamis*), and bigeye (*Thunnus obesus*) tunas in the Forum Fishing Agency member countries' Exclusive Economic Zones in the

WCPO using vessel-level data over the years 1997-2001. In general, the period 1997-2001 experienced precipitous changes in the entire tuna industry due to the introduction of a major process innovation, fishing on drifting floating aggregation devices (FADs) in 1997, coupled with a decline in fishing on free-swimming schools of tuna or on tunas that aggregate under drifting logs.<sup>4</sup> The Korean fleet, however, has largely remained focused on harvesting free-swimming schools of tuna and to a lesser extent, tunas aggregating under logs. The Korean fleet accounts for only a small proportion of the FAD fishing. The question arises as to whether the introduction of FADs had a substantive effect on the MFP growth of the Korean fleet.

The paper finds that due to the limited adoption of this process innovation (FADs) -- into the Korean fleet, MFP growth has been modest. The paper also demonstrates that failure to account for the resource stocks or the state of the environment leads to biased measures of MFP growth.

The balance of the paper is organized as follows. Section 2 presents the Malmquist productivity index incorporating stocks of natural resources and the environment. Section 3 discusses the empirical specification and data. Section 4 reports empirical results and Section 5 gives concluding remarks.

## **2. The Malmquist Productivity Index**

The multiproduct firm's stock-flow production technology represented by output distance functions is defined as:  $D_t(y_t, x_t, B_t, z_t) = \inf\{\lambda > 0 : (y_t/\lambda, x_t, B_t, z_t), S_t\}$ . The distance represents the smallest factor  $\lambda$  by which to deflate output so as to be feasible or producible with given  $x_t$ ,  $B_t$ , and  $z_t$  under period- $t$  technology. When there is a single

good produced,  $D_t(y_t, x_t, B_t, z_t) = y_t / f(x_t, B_t, z_t)$ .  $D_t(y_t, x_t, B_t, z_t)$  is non-decreasing, homogeneous of degree one in output, convex in  $y_t$  and non-decreasing in  $x_t$ , and jointly continuous in  $(y_t, x_t, B_t, z_t)$ , and it is the reciprocal of Farrell's radial measure of output-oriented technical efficiency (Färe, and Primont 1995).<sup>5</sup> The output distance function  $D_{t+1}(y_t, x_t, B_t, z_t)$  relates observed output in time t to the maximum attainable with period t+1 technology.

### *The Malmquist Productivity Index*

The Malmquist MFP index, introduced by Caves, Christensen, and Diewert (1982), uses distance functions and builds upon Malmquist (1953). The Malmquist output-oriented productivity for period-t technology can be written:

$$M = \frac{D_t(y_{t+1}, x_{t+1}, B_{t+1}, z_{t+1})}{D_t(y_t, x_t, B_t, z_t)} . \quad (1)$$

$M$  measures the MFP change between two data points by calculating the ratio of the distances of each data point relative to a common technology. If period t+1 has a higher level of productivity than is implied by the period-t technology, then  $M > 1$ .<sup>6</sup> Since two benchmark technologies for periods t and t+1 are not necessarily non-neutrally related or non-nested, the geometric mean is calculated (Caves *et al.* 1982):

$$M = \left[ \frac{D_t(y_{t+1}, x_{t+1}, B_{t+1}, z_{t+1})}{D_t(y_t, x_t, B_t, z_t)} \frac{D_{t+1}(y_{t+1}, x_{t+1}, B_{t+1}, z_{t+1})}{D_{t+1}(y_t, x_t, B_t, z_t)} \right]^{1/2} \quad (2)$$

The right-hand side of Equation (2) can be decomposed into the product of technical efficiency change and technical change (Nishimizu and Page 1982, Färe *et al.* 1994):

$$M = \frac{D_{t+1}(y_{t+1}, x_{t+1}, B_{t+1}, z_{t+1})}{D_t(y_t, x_t, B_t, z_t)} \left[ \frac{D_t(y_{t+1}, x_{t+1}, B_{t+1}, z_{t+1})}{D_{t+1}(y_{t+1}, x_{t+1}, B_{t+1}, z_{t+1})} \frac{D_t(y_t, x_t, B_t, z_t)}{D_{t+1}(y_t, x_t, B_t, z_t)} \right]^{1/2} \quad (3)$$

The ratio outside of the brackets in Equation (3) measures the change in relative technical efficiency – the change in the distance of observed production from best-practice production – between periods  $t$  and  $t+1$ . The term within the brackets is an index of technical change from period  $t$  to  $t+1$  and shows whether the best-practice frontier relative to the firm in question is improving, stagnant, or deteriorating.<sup>7</sup> When any component is larger (smaller) than unity, there is improvement (deterioration).

The best-practice firms establish the production frontier and the Farrell technical efficiency of all other firms is measured relative to this frontier. The time series of data then allows for estimation of technical progress (the movement of the frontier established by the best-practice firms) and changes in technical efficiency over time (the distance of the inefficient firms from the best-practice frontier) – “catching up” (Nishimizu and Page 1982, Färe, Grosskopf, Norris, and Zhang 1994).

#### *Capacity Utilization and Capital Utilization*

Productivity measures can be biased without accounting for variations in capacity utilization (CU) or capital utilization (Jorgenson and Griliches 1968, Morrison 1985). This discussion has focused on the fluctuation of economic activity over the business cycle, so that service flows are not always proportional to the capital stock. With fugitive natural resources, an additional spatial source of variation is introduced into utilization of the capital stock, the variation in time spent by the capital stock – the vessel, equipment, and gear – in searching for the resource prior to exploitation. This additional utilization in turn varies according to the fluctuations in demand, natural resource abundance and availability, and the environment. The approach of Jorgenson and Griliches (1968) incorporates the utilization of capital by measuring capital in the production technology

as utilized capital, rather than simply assuming that capital services are proportional to the capital stock.<sup>8</sup>

#### *Calculation of the Malmquist Productivity Index*

To calculate the index, we calculate the four component output distance functions, which will involve four linear programming programs for each producer in each pair of adjacent time periods. For example, the constant-returns-to-scale and output-oriented linear programming specification used to calculate  $D_t(\mathbf{y}_t, \mathbf{x}_t, \mathbf{B}_t, \mathbf{z}_t)$  for each firm  $k$  is (Färe, Grosskopf, and Roos 1995):

$$[D_t(\mathbf{y}_t, \mathbf{x}_t, \mathbf{B}_t, \mathbf{z}_t)]^{-1} = \max_{\phi, \lambda} \phi, \quad (4)$$

subject to:

$$-\phi \mathbf{y}_{kt} + \mathbf{y}_t \boldsymbol{\lambda} \geq \mathbf{0}$$

$$\mathbf{x}_{kt} - \mathbf{x}_t \boldsymbol{\lambda} \geq \mathbf{0}$$

$$\mathbf{B}_{kt} - \mathbf{B}_t \boldsymbol{\lambda} \geq \mathbf{0}$$

$$\mathbf{z}_{kt} - \mathbf{z}_t \boldsymbol{\lambda} \geq \mathbf{0}$$

$$\boldsymbol{\lambda} \geq \mathbf{0}$$

where  $\lambda$  are intensity variables which form the convex combinations of observed inputs and outputs, biomasses, and environmental variables, thereby forming the piecewise linear best-practice reference technology. The intensity variables provide the (variable) weights given to each activity or observation to which observed points are compared.

The remaining three linear programming programs are simple variants of this distance function,  $[D_{t+1}(\mathbf{y}_{t+1}, \mathbf{x}_{t+1}, \mathbf{B}_{t+1}, \mathbf{z}_{t+1})]^{-1}$ ,  $[D_t(\mathbf{y}_{t+1}, \mathbf{x}_{t+1}, \mathbf{B}_{t+1}, \mathbf{z}_{t+1})]^{-1}$ ,  $[D_t(\mathbf{y}_t, \mathbf{x}_t, \mathbf{B}_t, \mathbf{z}_t)]^{-1}$ ,

and  $[D_{t+1}(y_t, x_t, B_t, z_t)]^{-1}$ .<sup>9</sup> If there are K firms with T time periods, we need to calculate (3T-2) LP's for each firm (that is K\*(3T-2) LP's in the sample). The technology and the associated distance functions are independent of the units of measurement.

### 3. Empirical Specification

The vector of inputs,  $\underline{x}_t$ , comprises the vessel's (plant's) capital stock, measured in carrying capacity, and fishing effort, measured in the number of days spent fishing and searching. Fishing effort is not typical in production analyses, but it is consistent with the way managers and fishery researchers represent variable inputs (Kirkley, Squires, Strand 1995). Fishing effort thus represents energy, materials, and labor inputs, and is used because more explicit input measures, such as labor or fuel, are unavailable.<sup>10</sup> The flow of capital services is measured as the product of carrying capacity and fishing effort following the Jorgenson-Griliches approach to account for capital utilization. The measures of resource abundance are exploitable biomasses for all WCPO purse seine vessels for skipjack, yellowfin, and bigeye tunas. Environmental conditions are captured by measures of sea surface temperature (SST) in °F, where SST affects the aggregation of tunas in the Pacific (Sund, Blackburn, and Williams 1981).

Output or catch is specified as metric tons of yellowfin and bigeye tunas as one output and skipjack tuna as the second output. Yellowfin and bigeye tunas are not always separated (they look relatively similar as juveniles and bigeye catches are comparatively small) and catches of bigeye are often recorded as yellowfin catch. Hence, because of measurement error, we linearly aggregated yellowfin and bigeye catches into one output.

Skipjack is clearly distinguishable from yellowfin or bigeye, thus there is no measurement error from this source with this species.

### *Data*

The analysis uses individual vessel-level data and fishing effort data for catches in the WCPO. The catch, fishing effort (number of days fished and searched), vessel carrying capacity, and tuna stock abundance data are provided by the Oceanic Fisheries Programme (OFP) of the Secretariat of the Pacific Community (SPC). The years during which a vessel fished were determined from logsheet data held by the Oceanic Fisheries Programme of the SPC. Insufficient information is available to determine whether carrying capacity, which was initially reported to the Forum Fisheries Agency, may have changed during the time period covered (1997 to 2000) so that a vessel's carrying capacity value is the same for each year (even though the vessel may have been "stretched" to increase its size and carrying capacity).

Exploitable biomass estimates for the purse seine fishery for yellowfin, bigeye, and skipjack tunas were provided on a quarterly basis by the SPC<sup>11</sup> and are based on stock assessments undertaken for the Sixteenth Meeting of the Standing Committee on Tuna and Billfish. The quarterly estimates were converted into annual estimates by averaging over a given year. The vessel-level catch and effort data are collected by the OFP at the Secretariat of the Pacific Community (SPC) and pertain to the operations of the Korean fleet throughout the WCPO. The vessel carrying capacity data, also provided by the OFP of the SPC, were combined with the catch-and-effort data to provide the panel data set. SSTs for set of the net are taken from daily fishing logbooks of U.S. purse seine vessels, and pertain to west of 150°W latitude. These SSTs were averaged (a simple or

unweighted arithmetic average) over all sets, vessels, and areas to give mean annual SST's.<sup>12</sup>

**Table 1: Annual Summary Statistics of the Data per Vessel, 1997-2001**

Variable	1997	1998	1999	2000	2001	2002
Skipjack Catch (mt)	3,599	4,063	3,734	4,549	4,751	5,371
Yellowfin and Bigeye Catch (mt)	1,542	2,337	1,292	1,114	1,463	743
Vessel Carrying Capacity (mt)	1318	1318	1318	1318	1318	1318
Days fished and searched	240	277	281	241	257	265
Vessel Carrying Capacity * Days fished and searched	315,777	364,365	370,373	317,455	338,644	348,711
Sea Surface Temperature (°F)	85.59	84.30	83.80	83.60	84.90	83.68
Skipjack Biomass (mt)	1,357,793	2,096,661	2,663,134	2,663,134	2,054,939	2,210,299
Yellowfin Biomass (mt)	491,606	431,885	323,635	323,635	297,187	292,977
Bigeye Biomass (mt)	51,027	46,021	45,113	45,113	47,710	30,148

*Note:* Sample consists of 25 vessels for each year. mt = metric ton

#### 4. Empirical Analysis

In this section we use the methodology and data outlined in Sections 2 and 3 to estimate changes in the productivity of the Korean tuna purse seine fleet operating in the WCPO over the period 1997 to 2002 following Equation (3).

##### *Growth in Productivity, Technology, and Technical Efficiency*

The empirical results indicate that the mean annual MFP growth was marginally positive at 0.3 percent (Table 2).<sup>13</sup> This MFP growth was entirely due to technical change or process innovation (3.4 percent), since there was mean technical efficiency regress of -3.0 percent. Thus, the skippers of the best-practice vessels continued to innovate along with the adoption of improved vessel electronics or brailing systems, while the other

skippers and vessels failed to keep up with the rate of improvement of the innovating best-practice skippers and vessels. The results also demonstrate the variability of productivity growth across vessels, even within the same flag fleet.

Technical change represents the adoption of process innovations by the best-practice vessels of that production process.<sup>14</sup> Technical efficiency change represents the combined effects of at least two factors. First, process innovations such as FAD fishing or brailing systems tend to diffuse at different rates within a fleet, so that the change in technical efficiency captures, in part, the rate of diffusion of the innovation. (Diffusion occurs by number of vessels and, for FAD fishing, numbers of FADs deployed and sets for a given vessel.) For example, when diffusion is comparatively slow, laggards will tend to innovate more slowly than the best-practice vessels and hence will “fall behind” the expanding best-practice frontier defined by the innovation (Nishimizu and Page 1982). Second, technical efficiency change is also, in part, capturing changes in learning-by-doing (such as finding fish) with the diffused innovation, i.e. gaining proficiency with the diffused process innovation. This notion of a dynamic component to fishing skill extends the static concept of fishing skill identified by Kirkley, Squires, and Strand (1998) with technical efficiency.

Cumulated (chained) productivity change over 1997-2001 progressed by 1.4 percent. This productivity progress was entirely due to cumulated technical change or process innovation of 18.1 percent, which outweighed cumulated technical efficiency regress of 14.1 percent (Table 3).

After accounting for the effects from varying environmental conditions and the effects of changes in resource abundance, the picture emerges of some vessels

innovating, thereby shifting out the best-practice frontier and other vessels not innovating or innovating at a much slower rate. For these vessels failing to “catch up” to the expanding best-practice frontier, comparatively little learning occurs.

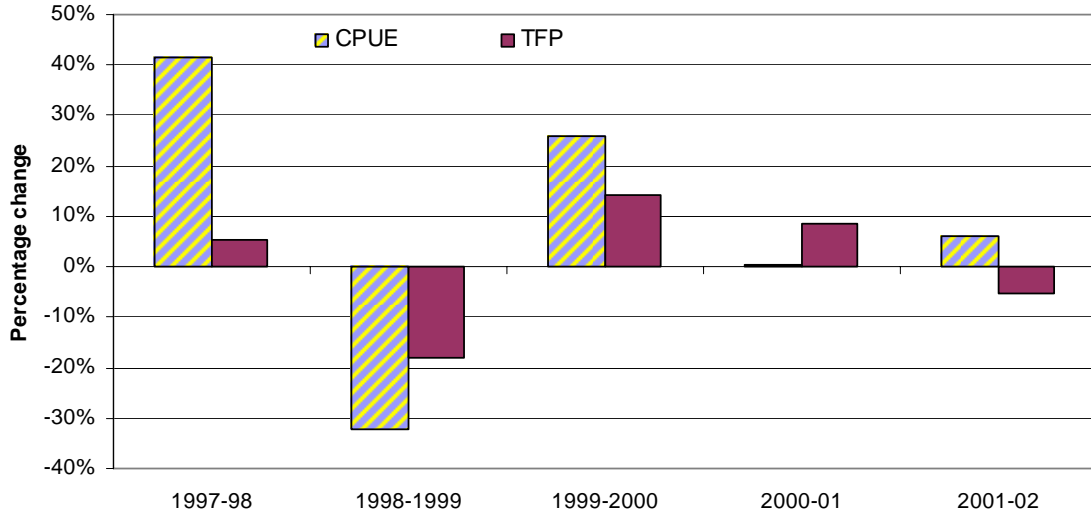
#### *Malmquist Multifactor productivity and CPUE*

Contrasting the Malmquist annual MFP growth, which control for the effects of changes in sea surface temperature and biomasses and include the effects of all inputs, with changes in the annual nominal catch-per-unit-effort (CPUE) values. They are simple partial productivity measures, provides strikingly dissimilar results (Figure 1). (The CPUE values are catch per fishing day and are based on the vessels that are included in the data set used in the analysis.) The nominal CPUE values in the period 1997-2000 display large swings as nominal CPUE increases substantially between 1997 and 1998, then declines in 1999 before increasing again in 2000. In contrast, the MFP changes between 1997 and 2000 are much more muted, particularly between 1997 and 1998. Estimated cumulative MFP change over the period 1997-2002 was 1.4 percent, that is, it is estimated that the 2002 the MFP of the Korean purse seine fleet was only 1.4 percent higher than it was in 1997. In contrast, nominal CPUE was in 2002 some 29 percent higher than in 1997 (Figure 2).

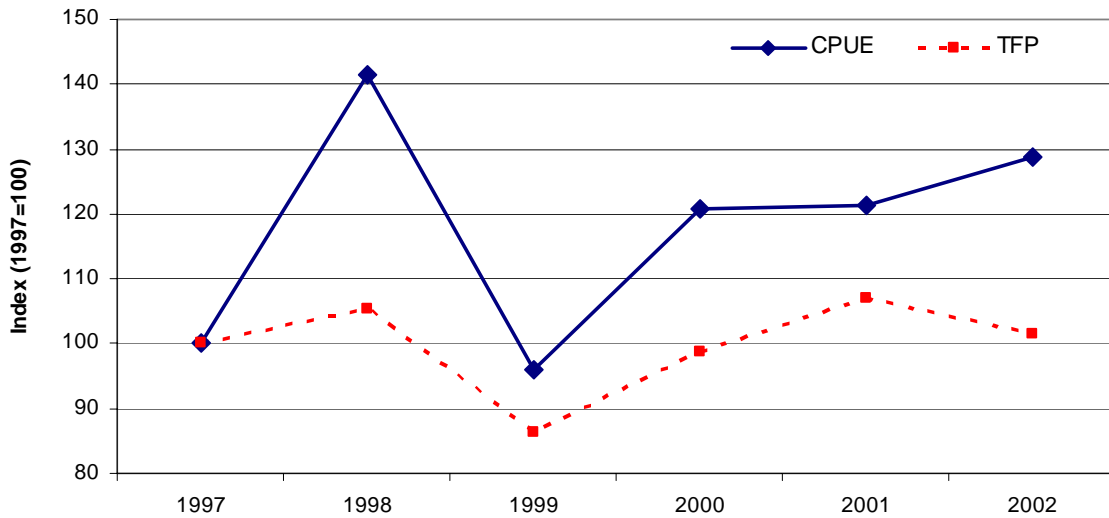
As previously outlined, annual mean MFP growth for the Korean purse seine fleet over the period 1997-2000 was marginally positive at just 0.3 percent. When the resource stock and environmental condition variables are excluded, the mean annual progress rates of aggregate productivity are -0.3 percent and 0.3 percent, respectively. However, excluding both the resource stock and the environment variables gives an annual progress rate of aggregate productivity of 11.2 percent, illustrating the bias and misleading results

that would otherwise result (Table 4). Accounting for changes in the abundance of resource stocks and the state of the environment reduces mean annual overall multifactor productivity growth from 11.2 percent to 0.3 percent.

**Figure 1: Annual nominal CPUE change and MFP change of Korean purse seine fleet in WCPO, 1997-2002**



**Figure 2: Cumulative nominal CPUE change and MFP change of Korean purse seine fleet in WCPO, 1997-2002**



**Table 2: Annual decomposition of multifactor productivity change accounting for capital utilisation**

	Technical Efficiency Change	Technical Change	Multifactor productivity Change
1997-98	0.928	1.136	1.053
1998-99	1.079	0.760	0.821
1999-00	0.964	1.184	1.142
2000-01	0.939	1.156	1.085
2001-02	0.947	1.000	0.947
Mean	0.970	1.034	1.003

*Note:* MFP and technical efficiency change are calculated relative to a constant-returns-to-scale technology following Equation (2) so that its interpretation is that it captures the change in maximal average product between t and t+1 (Grosskopf 2003). Annual values are geometric means of individual vessel values and overall mean is the geometric mean over individual years.

**Table 3: Cumulative (chained) multifactor productivity with adjustment for capital utilisation**

	Technical Efficiency Change	Technical Change	Multifactor productivity Change
1997	1.000	1.000	1.000
1998	0.928	1.136	1.053
1999	1.001	0.863	0.864
2000	0.965	1.022	0.987
2001	0.906	1.182	1.071
2002	0.859	1.181	1.014

**Table 4: Effects of resource stock and state of the environment upon annual aggregate multifactor productivity (MFP) growth**

	MFP	MFP without Resource Stock	MFP without Environmental Effect	MFP without Resource & Environment
1997-98	1.053	1.251	1.053	1.506
1998-99	0.821	0.751	0.821	0.872
1999-00	1.142	1.192	1.141	1.261
2000-01	1.085	1.059	1.085	0.903
2001-02	0.947	0.833	0.947	1.136
Mean	1.003	0.997	1.003	1.112

*Note:* Annual values are geometric means of individual vessel values and overall mean is the geometric mean over individual years.

## 5. Concluding Remarks

The paper demonstrated that without properly accounting for changes in the resource stocks and the state of the environment, biased measures of multifactor productivity will be obtained in fishing and other natural resource industries. Productivity growth must also account for changes in all inputs over time in order to obtain a complete and unbiased measure of productivity. Productivity measures accounting for only a single input, giving partial productivity such as CPUE (or catch per unit of effort), provide only a partial and incomplete measure of productivity growth over time. The paper also presented a non-parametric method of measuring multifactor productivity using distance functions, the Malmquist index, which readily accounts for unpriced changes in the resource stock and environment, and which does not require cost data. The approach was applied to a panel of Korean tuna purse seine vessels in the WCPO, where only modest growth of multifactor productivity was found, although growth in CPUE was vigorous.

Productivity growth is one of the most important, if not the most important, determinants of the growth in fishing capacity over time and represents one of the key challenges to managing fisheries. Without accurate measures of productivity growth in fishing industries, the extent of the excess capacity plaguing global fisheries cannot be properly assessed and appropriate conservation and management policies formulated.

The results are also of considerable geostrategic importance. Korea, along with the United States and Japan, are the high-cost producers of purse seine-caught tuna in the WCPO and their continued competitiveness – and hence survival and presence as flag state vessels – depends, in part, on continued productivity growth. The low-cost producers of Chinese Taipei (Taiwan), and increasingly China, may otherwise supplant

flag states that cannot remain competitive, and thereby increase their flag state's presence throughout the WCPO. Thus, governments throughout the WCPO are increasingly facing this issue.

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## Endnotes

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<sup>1</sup> Empirical studies of natural resource industries to evaluate productivity growth and technical change in natural resource industries accounting for the resource stock include Squires (1992), Jin, Thurnberg, Kite-Powell, and Blake (2002), and Hannesson (2006) who used Tornqvist index numbers, and Lasserre and Ouellette (1988), Campbell and Hand (1998), and Squires and Grafton (2000), who all used econometric techniques. Kirkley, Paul, Cunningham, and Costanzano (2004) examined embodied technical change although without explicitly accounting for the resource stock. Simpson (1999), like many studies of productivity and technical progress in natural resource industries, focused on extracted resources that serve as intermediate outputs rather than the actual resource exploitation phase. Fox, Grafton, Kirkley, and Squires (2002) included resource stocks in a decomposition of profits.

<sup>2</sup> Individually, firms under open access have a negligible impact upon the common resource stock in most instances. Location decisions by individual firms can affect local densities and availability of the common resource stock, particularly for demersal (bottom-dwelling) species or for threatened and endangered species, but not for highly migratory species such as the pelagic oceanic tunas. Collectively, firms do impact the resource stock. Nonetheless, within the traditional static MFP framework based on the theory of the firm, the resource stock can largely be viewed as non-discretionary and not as an input under the control of the individual firm. The state of the environment is a technological constraint, hence non-discretionary, and not an input *per se* under the control of an individual firm.

<sup>3</sup> For renewable resources, the approach is fundamentally static, since it implicitly assumes that management decisions and exploitation by individual firms do not measurably affect the resource stock over a short period of time. Thus, the approach is developed within the standard productivity literature framework and is not explicitly dynamic.

<sup>4</sup> Fishing Aggregator Devices (FAD) reduce searching time for fish, since the fish naturally aggregate under the FADs, and the FADs may have radio beacons attached, which the vessel uses to find the FADs. There has also been advances in the application of sonar and satellite technology (Itano 2003), which has contributed to MFP growth. The reduced searching time lessens variable inputs or reduced fishing effort expended for any quantity of fish caught, or increases catch for any level of variable input usage, thereby contributing to productivity growth. There are also higher success rates for sets on floating objects, such as FADs and logs, compared to sets on free-swimming schools that have a higher incidence of zero catch sets. In sum, more fish are caught with FADs for given variable input usage, trips are shorter, less time is spent searching for fish, and average catch rates per set are higher.

<sup>5</sup> Homogeneity of degree one in outputs implies  $D_t(\lambda y_t, x_t, B_t, z_t) = \lambda D_t(y_t, x_t, B_t, z_t)$  for any  $\lambda > 0$ .

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<sup>6</sup> Suppose the data point in period t+1 lay beyond the production possibility frontier or feasible production set defined by the period-t technology; then  $D_t(y_{t+1}, x_{t+1}, B_{t+1}, z_{t+1}) > 1$  (i.e.  $\lambda > 1$ ) to deflate this data point to the frontier. Similarly, suppose the data point in period t lay below the frontier or feasible production set defined by the period-t technology; then  $D_t(y_t, x_t, B_t, z_t) < 1$  (i.e.  $\lambda < 1$ ) to inflate this data point to the frontier. Then  $M = D_t(y_{t+1}, x_{t+1}, B_{t+1}, z_{t+1}) / D_t(y_t, x_t, B_t, z_t) > 1$

<sup>7</sup> The technical efficiency change indicates whether the observation has gotten closer or farther from the frontier over time. The first ratio inside the bracket captures technical change and evaluates the shift in the frontier at the data observed in period t+1, whereas the second term captures that shift evaluated at the data observed in period t. Also, as observed by Färe, Grosskopf, and Roos (1995), the period t and t+1 indices are equivalent only if the technology is Hicks output neutral, so that the output distance functions may be written as  $D_t(y_t, x_t, B_t, z_t) = A(t)D(y_t, x_t, B_t, z_t) \forall t$ . Taking the geometric mean avoids imposing this restriction or arbitrarily choosing one of the two technologies.

<sup>8</sup> Capital is a flow of services given by multiplying the capital stock by the amount of utilization. This Jorgenson-Griliches (1968) framework is based on capital utilization rather than capacity utilization (CU). It assumes that only a single stock of capital determines capacity, and does not recognize the importance of fixity for establishing the value of capital (or other fixed inputs). Instead, it directly adjusts the quantity of capital for utilization. Since there is utilization of a single capital stock, capacity and capital utilization are basically the same.

<sup>9</sup> See, for example, Färe, Grosskopf, Norris, and Zhang (1994), Färe, Grosskopf, and Roos (1995), Grosskopf (2003), who also discuss the issues associated with mixed period distance functions.

<sup>10</sup> Campbell and Hand (1998) argue that all inputs are effectively fixed once the vessel puts to sea. Catch then depends on the intensity of factor use during the time period, which is measured by the number of sets fished multiplied by the quantity of the fixed factor, i.e. services flow.

<sup>11</sup> Pers. com. John Hampton, Oceanic Fisheries Programme Manager, Secretariat of the Pacific Community (2004).

<sup>12</sup> Sea surface temperature (SST) was selected, in part, due to data availability. Logbooks, filled out for each set of the net by vessel skippers, contain SST for almost every set. Temperature affects the location and growth of primary producers (phyto- and zoo-plankton) upon which forage fish (e.g. sardines) feed. In turn, predators living higher on the food web, such as tunas and swordfish, feed upon these forage fish. Moreover, aggregation of the components of the food web occurs along temperature breaks in the ocean. That is, SSTs in the ocean are not uniform; instead, there are abrupt temperature breaks. Other environmental variables were not readily available from this or other data sources.

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<sup>13</sup> Subtracting 1 from a number in a table gives average increase or decrease per annum for the relevant time period and performance measure (Färe, *et al.* 1994). Multiplying by 100 then gives percentage annual change. The results are reported as symmetric geometric means, which is standard for Malmquist productivity measures and is what is routinely calculated by two of the most well-established software packages, DEAP and OnFront. It is also suggested by the literature such as Coelli, Rao, O'Donnell, and Battese (2005, 304-306). We used OnFront and simply applied its results following conventional practice. The asymmetrically weighted geometric mean issue will be one for future research, as a referee suggests.

<sup>14</sup> Matsumoto *et al.* (2000) and Shono *et al.* (2000) observe that most of the introduction or improvement in vessel electronics were made around 1990-91, so that much of these innovation effects on productivity growth may have already been accounted for by 1997, which was the beginning of this paper's study. Nonetheless, although there have not been many advances in "new" types of electronics in the last decade, significant improvements have occurred in traditional gear, particularly for sonar systems that are now closely integrated with GPS and Doppler current readings and for SIMRAD sonar systems in attempts to integrate computers to assist with species and size discriminations. The application of satellite technology has also played a role (Itano 2003). Another innovation is the introduction of Spanish style brailing (the catch handling and processing system), in which catch are brailed directly to recirculating brine holds cooled to approximately  $-9^{\circ}\text{C}$  by ammonia compressors and held in the same hold until unloaded or transshipped; this gives faster fishing operations and the potential for more sets per day and larger catches before spoilage.