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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ABSTRACT

Measures of multifactor productivity growth in natural resource industries are biased unless the effects on the environment are taken into account. 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 that fish for tunas in the western and central Pacific Ocean.

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 for industries for and natural resources, such as agriculture, mining, forestry, fisheries and power generation, that are directly affected by the environment. Environmental changes can include short-term events, such as precipitation, temperature and El Niño-Southern Oscillation episodes, medium-term (decadal-scale events), and long-term climate change. These changes in the state of the environment are unpriced, so they require treatment in MFP measures that are different from that for priced inputs and outputs.

Some attention has been devoted to environmental effects on productivity and economic growth in the environmental, resource and productivity literature, but

formal treatments in models of productivity growth and technical change have either overlooked environmental effects, or these ideas have not been 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 natural 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 natural 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 multifactor productivity growth in natural resource industries are biased unless the effects on the environment are taken into account. Disentangling productivity growth from changes in natural 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 over time 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 for which productivity growth and technical progress are viewed as enhancing the resource stock. For example, in the above-mentioned common resources such as fisheries, productivity growth and technical progress simply increase the rate of exploitation. Also, the costs of producing forest resources today are no longer limited to the costs of extraction; the costs of planting, growing and harvesting are now a significant part of the total cost of producing these resources (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 (SST) into the stock-flow production technology for a renewable common resource, marine fish.[1] Specifically, this paper develops output-oriented Malmquist indices of multifactor

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[1] 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 *et al.* (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 *et al.* (2004) examined embodied technical change, although without explicitly accounting for the resource stock. Simpson (1999), like many others who studied productivity and technical progress in natural resource industries, focused on extracted resources that serve as intermediate outputs, rather than on the actual resource exploitation phase. Fox *et al.* (2002) included resource stocks in a decomposition of profits.

productivity, technical change and technical efficiency, while accounting for changes in abundance of the fish stocks and the state of the environment, such as the SSTs. 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 natural resource stock (Squires 1992), so that, following Gordon (1954) and McFadden (1978), it becomes a technology shift variable.[2] We evaluate productivity in a framework developed from the neoclassical theory of the firm for which there is a stock-flow production technology with a common natural resource.[3] 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 fish stocks and states of the environment, such as climate and ecosystem services (*e.g.* nutrient flows and availability).

We evaluate productivity growth for a micro-level panel (combined cross-section and time-series data) of Korean purse-seine vessels that fish for tropical tunas (essentially at the plant level) harvesting common-pool skipjack (*Katsuwonus pelamis*), yellowfin (*Thunnus albacares*) and bigeye (*T. obesus*) tunas in the Exclusive Economic Zones of the member countries of the Forum Fisheries Agency (FFA), using vessel-level data for 1997-2002. In general, there were precipitous changes during 1997-2002 in the entire tuna industry, due to the introduction of a major process innovation, fishing on drifting fish-aggregating devices (FADs) in 1997, coupled with a decline in fishing on free-swimming schools of tuna and on tunas that aggregate under flotsam.[4] However, the focus of the Korean fleet has remained largely on free-swimming schools of tuna and, to a lesser extent, on tunas aggregating under flotsam. Only a small proportion of the total fishing effort on tunas associated with FADs is exerted by the Korean fleet. The question arises as to whether the introduction of FADs has 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. It also demonstrates that failure to account for the natural resource stocks or the state of the environment leads to biased measures of MFP growth.

2. THE MALMQUIST PRODUCTIVITY INDEX

The multiproduct firm's stock-flow production technology represented by output distance functions is defined as: $D_t(y_t, x_t, B_t, z_t) = \inf\{\lambda > 0(y_t/\lambda, x_t, B_t), S_t\}$. The distance represents the smallest factor λ by which to deflate output so as to be feasible or

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[2] Individual firms under open access, in most instances, have a negligible impact upon common resource stocks. Location decisions by individual firms can affect local densities and availability of common resource stocks, 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 be largely viewed as non-discretionary, rather than as an input under the control of the individual firm. The state of the environment is a technological constraint, and hence non-discretionary, and not an input *per se* under the control of an individual firm.

[3] 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.

[4] Fish-aggregating devices (FADs) reduce searching time for fish, since the fish naturally aggregate around the FADs, and the FADs may have radio beacons attached, which the vessels use to find the FADs. There have 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 reduces fishing effort expended for any quantity of fish caught, or increases the catch for any level of variable input usage, thereby contributing to productivity growth. Also, the success rates for sets on floating objects, such as FADs and flotsam, are greater than those for sets on free-swimming schools of tunas, which have a higher incidence of zero-catch sets. In summary, more fish are caught with FADs for given variable input usage; less time is spent searching for fish, and the average catches per set are greater.

producible with given x_t, B_t and z_t under period-t technology. When there is a single good produced, $D_t(y_t,x_t,B_t,z_t) = y_t/f(x_t,B_t)$. $D_t(y_t,x_t,B_t,z_t)$ is non-decreasing, homogeneous of degree-one in output, convex in y_t, 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).[5] 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 MFP index, introduced by Caves, Christensen and Diewert (1982), uses distance functions, and builds upon the work of Malmquist (1953). The Malmquist output-oriented productivity for period-t technology can be written:

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

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 $M>1$.[6] 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, Christensen and Diewert 1982):

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

The right 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):

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

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.[7] 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 (movement of the frontier established by the best-practice firms) and changes in technical efficiency over time (distance of the

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[5] 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 $\lambda > 0$.

[6] 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 $M = D_t(y_{t+1},x_{t+1},B_{t+1},z_{t+1})/D_t(y_t,x_t,B_t,z_t)>1$

[7] 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.

inefficient firms from the best-practice frontier)–"catching up" (Nishimizu and Page 1982, Färe *et al.* 1994).

3. CAPACITY UTILIZATION AND CAPITAL UTILIZATION

Productivity measures can be biased if variations in capacity utilization (CU) or capital utilization are not taken into account (Jorgenson and Griliches 1968, Morrison 1985). This discussion has focused on the fluctuation of economic activity over the business cycle, so that flows of services from the capital stock are not always proportional to the capital stock itself. With highly mobile fish, 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, abundance and availability of fish and changes in 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.[8]

3.1 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 $D_t(y_t, x_t, B_t, z_t)$ for each firm k is (Färe, Grosskopf and Roos 1995):

$$[D_t(y_t, x_t, B_t, z_t)]^{-1} = \max_{\phi, \underline{\lambda}} \phi, \tag{4}$$

subject to:

$$-\phi y_{kt} + y_t \lambda \geq 0$$

$$x_{kt} - x_t \lambda \geq 0$$

$$B_{kt} - B_t \lambda \geq 0$$

$$z_{kt} - z_t \lambda \geq 0$$

$$\lambda \geq 0$$

where λ are intensity variables which form the convex combinations of observed inputs and outputs, biomasses of fish stocks and environmental variables, such as the SSTs, 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, $[D_{t+1}(y_{t+1}, x_{t+1}, B_{t+1}, z_{t+1})]^{-1}$, $[D_t(y_{t+1}, x_{t+1}, B_{t+1}, z_{t+1})]^{-1}$, $[D_t(y_t, x_t, B_t, z_t)]^{-1}$ and $[D_{t+1}(y_t, x_t, B_t, z_t)]^{-1}$.[9] If there are K firms with T time periods, we need to calculate (3T-2) LPs for each firm (that is K*(3T-2) LPs in the sample). The technology and the associated distance functions are independent of the units of measurement.

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[8] 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 on 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.

[9] See, for example, Färe *et al.* (1994), Färe, Grosskopf and Roos (1995) and Grosskopf (2003), who also discuss the issues associated with mixed-period distance functions.

TABLE 1
Annual summary statistics of the data per vessel, 1997-2002

Variable	1997	1998	1999	2000	2001	2002
Skipjack catch (tonnes)	3 599	4 063	3 734	4 549	4 751	5 371
Yellowfin and bigeye catch (tonnes)	1 542	2 337	1 292	1 114	1, 463	743
Vessel carrying capacity (tonnes)	1 318	1 318	1 318	1 318	1 318	1 318
Days fished and searched	240	277	281	241	257	265
Vessel carrying capacity x days 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 (tonnes)	2 011 169	3 036 725	4 546 500	3 434 138	2 876 063	2 787 675
Yellowfin biomass (tonnes)	517 188	488 124	439 500	416 545	376 969	374 304
Bigeye biomass (tonnes)	96 511	83 851	84 445	76 633	80 843	65 009

The sample consists of 25 vessels for each year. °F = (°C x 1.8) + 32. The values in the last three lines are the averages of the exploitable biomasses for the fish available to the fishery for tunas associated with floating objects and that for free-swimming schools of tunas.

3.2 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 searching for fish. Fishing effort is not typical in production analyses, but it is consistent with the way managers and fishery scientists represent variable inputs (Kirkley, Squires and 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.[10] The flow of capital services is measured as the product of carrying capacity and fishing effort, following the Jorgenson-Griliches (1967) approach to account for capital utilization. The measures of resource abundance are exploitable biomasses for all purse-seine vessels that fish in the WCPO for skipjack, yellowfin and bigeye tunas. Environmental conditions are captured by measures of SST in degrees Fahrenheit, where SST affects the aggregation of tunas in the PacificOcean (Sund, Blackburn and Williams 1981).

Output or catch is specified as tonnes of yellowfin and/or bigeye tunas as one output and tonnes of skipjack tuna as the second output. Yellowfin and bigeye tunas are not always recorded separately, as the juveniles, which make up the majority of the purse-seine catches, are similar in appearance. The catches of yellowfin far exceed those of bigeye, so mixed catches of the two species are often recorded as yellowfin. Hence, because of measurement error, we linearly aggregated yellowfin and bigeye catches into one output. Skipjack are clearly distinguishable from yellowfin or bigeye, and the prices paid for skipjack are les than those paid for yellowfin and bigeye, so the catches of this species are always recorded separately.

3.2.1 Data

The analysis uses individual vessel-level data and fishing effort data for catches in the WCPO. The catch, fishing effort (number of days spent searching for fish), vessel carrying capacity and estimates of abundance of the three species of tuna were 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 OFP. Insufficient information is available to determine whether carrying capacity, which was initially reported to the FFA, may have changed during the time period covered (1997-2002) so that the carrying capacities of the vessels were assumed to have been the same during each year, even though some vessels may have been "stretched" to increase their carrying capacities).

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[10]   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 made multiplied by the quantity of the fixed factor, *i.e.* services flow.

Exploitable biomass estimates for the purse-seine fishery for skipjack, yellowfin and bigeye, tunas, which were provided on a quarterly basis by the OFP[11], are based on the stock assessments (Langley, Ogura and Hampton 2003, Hampton and Kleiber 2003 and Hampton *et al.* 2003). The quarterly estimates were converted into annual estimates by summing the quarterly catches for each year. The vessel-level catch and effort data, which are collected by the OFP, pertain to the operations of the Korean fleet throughout the WCPO. The vessel carrying capacity data, also provided by the OFP, were combined with the catch and effort data to provide the panel data set. The SSTs for each set of the nets are taken from the logbooks of United States purse-seine vessels that operate west of 150°W latitude. The arithmetic average of these SSTs for all sets of all vessels in all areas of the WCPO are used as mean annual SSTs.[12]

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

3.2.2 Growth in productivity, technology and technical efficiency
The empirical results indicate that the mean annual growth in MFP was marginally positive at 0.3% (Table 2).[13] This MFP growth was due entirely to technical change or process innovation (3.4%), since there was mean technical efficiency regresion of -3.0%. Thus, the managers or captains of the best-practice vessels continued to innovate with the adoption of improved vessel electronics or brailing systems, while the managers or captains of the other vessels failed to keep up with the innovations of the best-practice 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.[14] Technical efficiency change represents the combined effects of at least two factors. First, process innovations, such as fishing for tunas associated with FADs or improved brailing systems tend to diffuse at different rates within a fleet, so that the change in technical efficiency captures, in part, the

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[11] Pers. com., John Hampton, Manager, Oceanic Fisheries Programme, Secretariat of the Pacific Community (2004).

[12] Sea-surface temperature (SST) was selected, in part, due to data availability. The logbooks of the vessels contain SST records for almost every set. Temperature affects the location and growth of primary producers (phyto- and zooplankton) upon which forage fish (*e.g.* small pelagic fish) feed. In turn, predators living higher on the food web, such as tunas and billfishes, feed upon these forage fish. Moreover, aggregation of the components of the food web occurs along temperature breaks in the ocean. That is,variation in the SSTs in the ocean are not always gradual; instead, there are abrupt temperature breaks. Other environmental variables were not readily available from this or other data sources.

[13] 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 the percentage of 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 best-established software packages, DEAP and OnFront. It is also suggested by economists such as Coelli *et al*. (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.

[14] Matsumoto *et al*. (2000) and Shono *et al*. (2000) observed that most of the introduction or improvement in vessel electronics were made around 1990-1991, so that much of these innovation effects on productivity growth may have already been accounted for by 1997, which was the initial year of the period covered by the 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 catches are brailed directly to recirculating brine holds cooled to approximately –9°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 greater catches before spoilage.

TABLE 2
Annual decomposition of multifactor productivity change accounting for capital utilization

	Technical efficiency change	Technical change	Multifactor productivity change
1997-1998	0.928	1.136	1.053
1998-1999	1.079	0.760	0.821
1999-2000	0.964	1.184	1.142
2000-2101	0.939	1.156	1.085
2001-2002	0.947	1.000	0.947
Mean	0.970	1.034	1.003

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). The annual values are geometric means of individual vessel values, and the overall mean is the geometric mean over the individual years.

TABLE 3
Cumulative (chained) multifactor productivity with adjustment for capital utilization

	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 natural 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 and environment
1997-1998	1.053	1.251	1.053	1.506
1998-1999	0.821	0.751	0.821	0.872
1999-2000	1.142	1.192	1.141	1.261
2000-2001	1.085	1.059	1.085	0.903
2001-2002	0.947	0.833	0.947	1.136
Mean	1.003	0.997	1.003	1.112

The annual values are geometric means of individual vessel value, and the overall mean is the geometric mean over individual years.

rate of diffusion of the innovation. (Diffusion occurs by number of vessels and, for FAD fishing, numbers of FADs deployed and sets on FADs by a given vessel.) For example, when diffusion is comparatively slow, the 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 during 1997-2002 progressed by 1.4%. This productivity progress was due entirely to cumulative technical change or process innovation of 18.1%, which outweighed cumulated technical efficiency regression of 14.1% (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 to the best-practice frontier and other vessels not innovating or innovating at a much slower rate. Comparatively little learning takes place for the vessels failing to "catch up" with the expanding best-practice frontier.

3.2.3 *Malmquist multifactor productivity and CPUE*

Contrasting the Malmquist annual MFP growth, which control for the effects of changes in SST and biomasses and include the effects of all inputs, with changes in the annual nominal values of catch per unit effort (CPUE). They are simple partial productivity measures, providing strikingly dissimilar results (Figure 1). (The CPUE values are catches per day of searching, and are based on the vessels that are included in the data set used in the analysis.) The nominal CPUE values for the 1997-2000 period display large swings, as the nominal CPUE increased substantially between 1997 and 1998, declined between 1998 and 1999 and then increased again between 1999 and 2000. In contrast, the MFP changes between 1997 and 2000 were much more muted, particularly between 1997 and 1998. The estimated cumulative MFP change during the 1997-2002 period was 1.4%, that is, it is estimated that the 2002 the MFP of the Korean purse seine fleet was only 1.4% greater than it was in 1997. In contrast, the nominal CPUE was about 29% greater in 2002 than in 1997 (Figure 2).

FIGURE 1
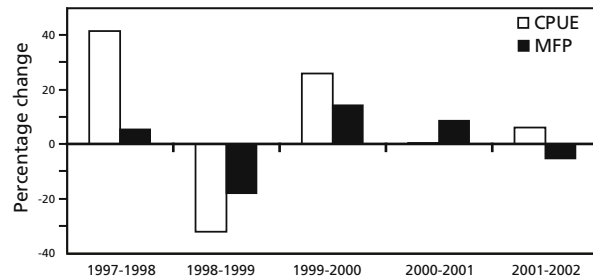**Annual changes in nominal CPUE and MFP of the Korean purse-seine fleet in the WCPO during 1997-2002**

FIGURE 2
Cumulative changes in nominal CPUE and MFP of the Korean purse-seine fleet in the WCPO during 1997-2002

As previously outlined, the annual mean MFP growth for the Korean purse-seine fleet during the 1997-2000 period was marginally positive at just 0.3%. When the natural resource stock and environmental condition variables are excluded, the mean annual progress rates of aggregate productivity are -0.3% and 0.3%, respectively. However, excluding both the natural resource stock and the environmental variables gives an annual progress rate of aggregate productivity of 11.2%, illustrating the bias and misleading results that would otherwise result (Table 4). Accounting for changes in the abundance of natural resource stocks and the state of the environment reduces the mean annual overall multifactor productivity growth from 11.2% to 0.3%.

4. CONCLUDING REMARKS

This paper demonstrates that measures of multifactor productivity growth in natural resource industries are biased unless changes in the abundance of the fish stocks stocks and the effects of changes in the environment are taken into account. Furthermore, all changes in inputs over time must be taken into account to obtain complete and unbiased measures of productivity. Productivity measures such as CPUE, which that take into account only a single input (effort), provide incomplete measures of growth in productivity over time. This paper also presents a non-parametric method of measuring multifactor productivity, using a distance function, 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 group of Korean purse-seine vessels that fish for tunas in the WCPO, where only modest growth of multifactor productivity was found, even though the CPUE increased substantially.
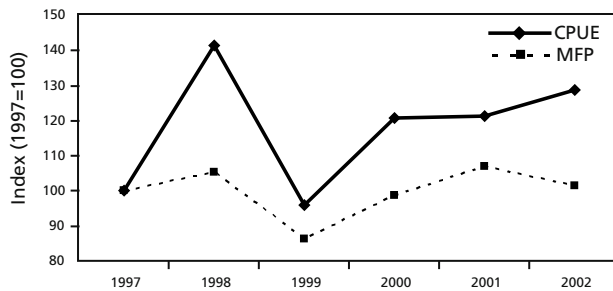
Productivity growth is one of the most important, if not the most important, determinants of the growth in fishing capacity over time, and represents one of the key challenges to managing fisheries. Without accurate measures of productivity growth in fishing industries, the extent of the excess capacity in global fisheries cannot be properly assessed, and appropriate conservation and management policies cannot be formulated.

The results are also of considerable political importance. The Republic of Korea, the United States and Japan, are high-cost producers of purse seine-caught tuna in the WCPO, and their continued competitiveness–and hence continued presence as flag-state vessels–depends, in part, on continued productivity growth. The lower-cost producers *e.g.* Chinese Taipei and the Peoples Republic of China, may otherwise overtake them, and thereby increase the the presence of those flag states in the WCPO.

5. ACKNOWLEDGEMENTS

6. REFERENCES

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