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PRIVATE PROPERTY AND ECONOMIC EFFICIENCY: A STUDY OF A COMMON-POOL RESOURCE*

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Abstract

The British Columbia halibut fishery provides a natural experiment of the effects of ''privatizing the commons.'' Using firm-level data from the fishery 2 years before private harvesting rights were introduced, the year they were implemented, and 3 years afterward, a stochastic frontier is estimated to test for changes in technical, allocative, and economic efficiency. The study indicates that (1) the short-run efficiency gains from privatization may take several years to materialize and can be compromised by restrictions on transferability, duration, and divisibility of the property right; (2) substantial long-run gains in efficiency can be jeopardized by preexisting regulations and the bundling of the property right to the capital stock; and (3) the gains from privatization are not just in terms of cost efficiency but include important benefits in revenue and product form.

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> For that which is common to the greatest number has the least care bestowed upon it. Everyone thinks chiefly of his own, hardly at all of the common interest; and only when he is himself concerned as an individual. (ARISTOTLE, *Politics*, bk. 2, ch. 3, p. 27)

I. INTRODUCTION

THE structure of property rights has long been considered one of the most important factors affecting economic development and efficiency. For common-pool resources, where yields are rivalrous and use is only partially excludable, the absence of controls over access leads to the ''tragedy of the commons.'' Fisheries provide the classic case of open access,[1] where market failures arise, in part, because agents are unable to contract to exclude others and prevent rent dissipation.[2]

One solution to the problems of open access is the ''privatization of the commons'' or the creation of individual private property rights for common-pool resources. If transactions costs are zero, there is no strategic behavior, information is perfect, and the distribution of assets does not affect the marginal valuation of resources, the Coase Theorem implies that private property rights ensure efficiency. Limitations to the dimensions of private property rights, however, may result in firms optimizing such that their costs may not be minimized for given levels of output.[3]

Despite the growing use of private property to help solve common-pool externalities, such as air pollution, global warming, and the overharvesting of fish stocks, few empirical studies exist that test for changes in efficiency due to private property rights.[4] Instead, the literature has used comparisons, qualitative evidence, and descriptions to evaluate whether the theoretical benefits of private property have been realized. By contrast, this paper uses

[1] H. Scott Gordon, The Economic Theory of a Common Property Resource: The Fishery, 62 J. Pol. Econ. 124 (1954).

[2] Steven N. S. Cheung, The Structure of a Contract and the Theory of a Non-exclusive Resource, 13 J. Law & Econ. 49 (1970).

[3] Louis De Alessi, Property Rights, Transactions Costs, and X-Efficiency: An Essay in Economic Theory, 73 Am. Econ. Rev. 64 (1983).

[4] Surprisingly, very few empirical studies compare efficiency differences across property regimes. Richard J. Agnello & Lawrence P. Donnelley, Property Rights and Efficiency in the Oyster Industry, 18 J. Law & Econ. 521 (1975), provides one of the first studies in fisheries and showed that U.S. states with private property regimes had significantly higher average labor productivity in oyster production than states with limited-user open access regimes. The first empirical study that tests for changes in efficiency in the *same* common-pool resource, following privatization of the property right, is R. Quentin Grafton, Dale Squires, & Kevin J. Fox, Common Property, Private Rights and Economic Efficiency (Working Paper No. 9508E, Univ. Ottawa, Dep't Econ. 1995).

data from a natural experiment involving a common-pool resource to analyze the changes in a fishery following the introduction of private harvesting rights. Moreover, the paper examines the implications of attenuated rights on efficiency and the effects of different property rights characteristics on efficiency and producer surplus of firms. The results provide insights into how private rights may affect firm behavior and the expected benefits of ''privatizing the commons.''

II. Property Rights and Efficiency

Property rights are the societally accepted rights of individuals or groups of individuals to exploit assets for their benefit, with at least a partial right to exclude others. These rights may be described by their divisibility, exclusivity, transferability, duration, quality of title, and flexibility.[5] If one or more of these characteristics is attenuated, the benefits of incentive-based approaches for managing common-pool resources may be diminished.

Divisibility describes the extent to which the right can be partitioned, such as the division of surface and mineral rights for land. Exclusivity encompasses the notion of how an asset or resource can be used as well as the ability to restrict its use by others. It may include the right of access and to enjoy (*ius utile*), the right of withdrawal (*ius fruendi or usufructus*), and the right to prevent interference (*ius excludendi*). Transferability (*ius disponendi*) refers to the ease by which owners may trade, gift, or bequeath the property right. Duration encompasses the notion of how long the property right exists, such as whether it expires at the end of every year or is valid in perpetuity. Quality of title (*ius possidendi*) represents how well the property right is specified and includes the notions of possession and ownership (*de facto* and *de jure*).[6] Flexibility, the last characteristic, refers to the ability of the property right to accommodate changes in the resource and circumstances of the owner(s).

Various types of property rights with different characteristics have been used to address common-pool resource externalities and include the community management (*res communes*) of fisheries.[7] The coastal fisheries of

[5] These characteristics have been described by various authors including Anthony D. Scott & James Johnson, Property Rights: Developing the Characteristics on Interests in Natural Resources, in Progress in Natural Resource Economics (Anthony D. Scott ed. 1985); Richard A. Posner, Economic Analysis of Law (1986); and Rose Anne Devlin & R. Quentin Grafton, Economic Rights and Environmental Wrongs: Property Rights for the Common Good (1998).

[6] We are grateful to Chris Stone for making us aware of the Roman law definitions. The description of the characteristics comes from Devlin & Grafton, *supra* note 5.

[7] Many successful examples of community-managed fisheries exist, some of which are described in Common Property Resources: Ecology and Community-Based Sustainable Development (Fikret Berkes ed. 1989); Jean-Marie Baland & Jean-Philippe Platteau, Halting

Japan, in particular, illustrate how communities can effectively manage resources in a sustainable way and provide substantial benefits to the fishers through a mix of community and private rights.[8] Japan's coastal fisheries appear to satisfy the conditions for enduring community rights: well-defined geographical boundaries for the resource, rules of access and withdrawal that are accepted by the community and that are tailored to the resource and institutions, some monitoring and enforcement of rules with graduated sanctions against transgressors, resolution mechanisms for disputes among members, participation of most resource users in changes to collective rules, and recognition by outside authorities of the collective rights.[9]

The ability of fishing cooperatives or communities to successfully manage marine resources can be undermined by existing regulations, such as antitrust legislation in the United States[10] or regulations that undermine common-law traditions and existing property rights.[11] Where states have regulated fisheries and controls have been imposed over access with limits on the type and quantity of inputs, they have often failed to create a desirable property right or address the externalities prevalent in fisheries.[12]

In response to past failures in state regulated fisheries, alternative instruments, which include individual harvesting rights called individual transferable quotas (ITQs), are becoming increasingly popular as a means to increase efficiency and returns to fishers. Individual transferable quotas, in various forms, have been introduced in three U.S. fisheries and such countries as Canada, New Zealand, Iceland, Australia, and the Netherlands.[13] The principal advantage of individual harvesting rights is greater exclusivity in exploitation. Individual harvesting rights are not, however, a complete property right. For instance, ITQs provide a right over only the flow of the

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Degradation of Natural Resources: Is There a Role for Rural Communities? (1996); Elinor Ostrom, Governing the Commons: The Evolution of Institutions for Collective Action (1990); and Elinor Ostrom, Roy Gardner, & James Walker, Rules, Games, and Common-Pool Resources (1994).

[8] Kenneth Ruddle, Solving the Common-Property Dilemma: Village Fisheries Rights in Japanese Coastal Waters, in Common Property Resources: Ecology and Community-Based Sustainable Development (Fikret Berkes ed. 1989); Tadashi Yamamoto, Development of a Community-Based Fishery Management System in Japan, 10 Marine Resource Econ. 21 (1995).

[9] Ostrom, *supra* note 7.

[10] Bruce Yandle, Antitrust and the Commons: Cooperation or Collusion? 3 Indep. Rev. 37 (1998); Terry L. Anderson & Donald R. Leal, Fishing for Property Rights to Fish, in Taking the Environment Seriously (Roger E. Meiners & Bruce Yandle eds. 1993).

[11] Elizabeth Brubaker, Property Rights in the Defence of Nature (1995).

[12] Ralph E. Townsend, Entry Restrictions in the Fishery: A Survey of the Evidence, 66 Land Econ. 359 (1990); Michael De Alessi, Fishing for Solutions (1998).

[13] R. Quentin Grafton, Dale Squires, & James E. Kirkley, Private Property Rights and the Crises in World Fisheries: Turning the Tide? 14 Contemp. Econ. Pol'y 90 (1996).

resource and not the stock of fish and thus do not give a property right over the ocean environment.[14] Further, in all ITQ jurisdictions some limits have been placed on the characteristics of the property rights, especially their duration, transferability, and divisibility.

Individual harvesting rights have the potential to change both the costs and revenues of fishers. In the short run, the creation of an exclusive property right may mean that other regulations designed to restrict the harvest of the fishing fleet may be redundant. Thus, with individual output controls, the length of the fishing season may be increased. Coupled with transferability of the property right, harvesting rights should also help fishers to adjust their scale of operations to maximize their profits. A reduction in the "race to fish," because of ITQs, can reduce spoilage and mishandling of fish that is common in fisheries with very restricted fishing seasons. Thus ITQs have the potential to increase the value of the product landed by fishers and their producer surplus.

Depending on the fishery, fewer regulations on harvesting practices may also enable fishers to better adjust their mix of inputs to minimize costs for a given level of output. Given that the gear and vessels form nonmalleable capital in many fisheries, ITQs also offer the potential long-run benefit that fishers can adjust their vessels and equipment to an optimal size. Thus, depending on the former restrictions on inputs, one might expect ITQs to lead to improvements in allocative efficiency (the desirable mix of inputs) and technical efficiency (the desirable level of all inputs) over both the short and long run.

III. The Common-Pool Resource

To test for changes in firm behavior, efficiency, and producer surplus following the introduction of private property rights, we examine the British Columbia (BC) halibut fishery. Since 1923 management of the Pacific halibut fishery has been assisted by the International Pacific Halibut Commission (IPHC), a body established by the United States and Canada. The IPHC provides recommendations to both governments about area-specific fishing seasons, the total catches for all the fishing regions along the Pacific coast, and minimum size limits of the fish allowed to be caught.

[14] Michael Markels, Jr., Fishing for Markets: Regulation and Ocean Farming, 18 Regulation 73 (1995), discusses the benefits of privatizing large areas of the ocean which can then be fertilized to increase phytoplankton and increase fish harvests. Exclusive property rights are required so that the people making the investment in fertilizers can reap the benefits. A recent exclusive agreement between a private company and the Republic of the Marshall Islands gives the company the option to fertilize 800,000 square miles of open ocean in payment of a royalty dependent on the amount of fish harvested (Michael Markels, Jr., Farming the Oceans: An Update, 21 Regulation 9 (1998)).

Following a protocol between the two governments in 1979, the harvesting of halibut in Canadian waters has been restricted to Canadian fishers and the number of vessels limited to 435, the number of halibut fishing licenses. Limited transferability of licenses is permitted provided that the vessel to which the license is being transferred is no more than 10 feet longer in size. The ''stacking'' of licenses, however, is prohibited, and only one halibut license per vessel is permitted. In addition to halibut fishing licenses, the fishery has also been regulated by a total allowable catch (TAC) for the fleet, a limited fishing season, restrictions on the type of gear that can be used to harvest halibut, and minimum fish sizes. Most of the halibut fleet also participates in other ground fisheries and the salmon fisheries.

A. Fishing Practices

Halibut (*Hippoglossus stenolepis*) are a long-living and highly migratory species found from northern California to Alaska and are principally caught by longline gear. Longlining involves the setting of baited hooks laid at depths of 30–300 meters that are attached to ''skates,'' or shorter fishing lines, which are connected to a main fishing line and a series of buoys. After setting the lines, which are left to ''soak'' for 6–10 hours and sometimes up to 24 hours, the skates and fish are hauled on board. The harvested fish are gutted, after first being stunned on the head, and are packed in ice and delivered directly to processors. Captains can alter the level and composition of the catch by deciding where to fish, the season and depth of fishing, length of lines, type of bait, hook size, spacing of hooks on the lines, and the time the gear spends in the water. Catch size and species composition vary with expected halibut prices, biological abundance, seasonality, and other factors.

B. The ''Derby'' Fishery

Fishing effort increased over the 1980s with the number of vessels actively fishing for halibut rising from 333 to 435 over the decade. This increase, as shown in Table 1, was coupled with a rise in the number of crew per vessel and the use of more fishing gear and a longer time spent fishing per fishing day. By 1990, almost 50 percent more halibut was caught (with a fishing season per vessel of 6 days) than in 1980, when the fishing season was 65 days long.[15] Increased fishing effort contributed to a 12-fold increase

[15] In 1990, fishers were able to harvest halibut in two out of three designated ''openings.'' Each vessel could only fish a total of 6 days despite the fact that the fishing season was officially 10 days long.

TABLE 1

Season Length, Number of Active Fishing Vessels, and Total Catch in the British Columbia Halibut Fishery

Year	Season Length (days)	Number of Active Vessels	Total Catch (pounds)
1980	65	333	5,650,447
1981	58	337	5,654,856
1982	61	301	5,524,783
1983	24	305	5,416,757
1984	22	334	8,276,152
1985	22	363	9,587,902
1986	15	417	10,240,471
1987	16	424	12,251,086
1988	14	435	12,859,562
1989	11	435	10,738,715
1990	6	435	8,569,367
1991	214	433	7,189,273
1992	240	431	7,630,198
1993	245	351	10,560,141
1994	245	313	9,900,958
1995	245	294	9,499,717
1996	245	281	9,499,717

Sources.—Richard M. Porter, Structural and Market Consequences of Harvest Quotas in Canada's Pacific Halibut Fishery (paper presented at the conference Fisheries Population Dynamics and Management, Univ. Washington 1996); Paul MacGillivray, Experience with Individual Vessel Quotas in the British Columbia Halibut Fishery (paper presented at the conference Managing a Wasting Resource: Would Quotas Solve the Problems Facing the West Coast Salmon Fishery? Vancouver, May 30 and 31, 1996); Bruce R. Turris, personal communications (1997); Mark Herrmann, Estimating the Induced Price Increase for Canadian Pacific Halibut with the Introduction of the Individual Vessel Quota Program, 44 Can. J. Agric. Econ. 151 (1996).

in the average catch per day for the whole fleet from 1980 to 1990 and a tripling of the average landings per trip per vessel.[16]

As a result of the increased fishing pressure, the IPHC reduced the length of the fishing season throughout the 1980s to try to prevent the TAC of halibut from being exceeded. Over the entire period, the 435-vessel limit on the number of vessels allowed to fish halibut failed to control fishing effort and, instead, the length of the fishing season provided the constraint to ensure the TAC was not exceeded.[17] The objective in setting the TAC

[16] Richard M. Porter, Structural and Market Consequences of Harvest Quotas in Canada's Pacific Halibut Fishery (paper presented at the conference Fisheries Population Dynamics and Management, Univ. Washington 1996).

[17] The TAC itself is set by the IPHC using catch-at-age methods and data on catch, catch per unit of effort, and surveys over defined areas of the Pacific coast. Further details are provided in Terrance J. Quinn II, Richard B. Deriso, & Stephen H. Hoag, Methods of Popula-

was to fix exploitation rates between 20 and 25 percent of the available biomass so as to ''maintain halibut stock within its historical range.''[18] Achieving this objective was, and is, complicated by many uncertainties about the population dynamics of halibut, the factors that determine recruitment, and by-catch mortalities of halibut in other fisheries.

By the late 1980s, a reduced fishing season had increased fishing intensity and sometimes resulted in skates from different vessels being laid over the same area. Such practices increased the damages to lines and resulted in ''ghost fishing,'' whereby lost fishing gear continues to catch fish. A very short fishing season also encouraged fishers to catch halibut in unfavorable weather conditions and reduced safety at sea. Moreover, a short fishing season provided the incentive to fishers to maximize their landings over just few days, which in turn compromised product quality because fishers were more concerned in landing as much halibut as possible in the limited time available. In addition, catching and processing the entire catch in just a few days limited the marketing opportunities and the bargaining power of fishers to negotiate higher prices for their product from processors.

A drop in the total catch from 1988 to 1990 significantly reduced revenues to the halibut fleet and precipitated a crisis in the fishery. In 1988 a small group of halibut fishers requested the regulator, the Canadian Department of Fisheries and Oceans (DFO), to introduce individual harvesting rights in the fishery. Following extensive discussions between fishers and a vote in 1990, in which 70 percent of the fishers who responded supported the introduction of individual harvesting rights, the regulator introduced a 2-year trial program of individual vessel quotas (IVQs) in 1991.

C. The IVQ Fishery

Individual vessel quotas, designated as a percentage of the TAC, were allocated *gratis* to all license holders and calculated using a formula whereby 30 percent of the initial allocation was based on the length of a vessel and 70 percent on the best catch over the previous 4 years. The allocation formula tended to penalize ''highliners'' or captains who consistently outperformed the halibut fleet and benefited fishers with larger vessels, as well as marginal fishers who may have had just one successful year out of four.[19] To ensure exclusivity of the property right, fishers agreed to pay a landing charge to cover the costs of monitoring so as to discourage

tion Assessment of Pacific Halibut (Int'l Pacific Halibut Commission Scientific Rep. No. 72, 1985).

[18] Int'l Pacific Halibut Commission, Annual Report 1996, at 24 (1997).

[19] Keith E. Casey *et al.*, The Effects of Individual Vessel Quotas in the British Columbia Halibut Fishery, 10 Marine Resource Econ. 211 (1995).

persons from violating the fishing regulations. In December 1992, at the end of the trial period, over 90 percent of all responding halibut quota holders voted to continue with IVQs.

A concern among some fishers about the possibility of concentration of quota by processing companies and larger vessels, worries about the social impact of quotas, and the desire to go back to the status quo should IVQs prove unsuccessful led to a prohibition on quota trading over the initial 2-year trial period, except when the quota was sold with the corresponding vessel and license. A prohibition on transfers in the 2-year trial period was also considered the best way to ensure a majority vote by halibut fishers in favor of the initial introduction of IVQs because it separated the contentious issue of transferability from the question of whether or not individual harvesting rights should be introduced.[20]

The allocation of individual harvest rights for each vessel eliminated the need for a short fishing season, which was previously required to ensure that the TAC was not exceeded. Thus the introduction of IVQs resulted in an extension of the fishing season from just 6 days per vessel in 1990 to 214 days in 1991 and 245 days from 1993 onward. A change in the length of the fishing season, however, did not immediately lead to a dramatic shift as to when or where halibut were caught, which suggests that fishers may have needed some time to adjust to IVQs and the longer fishing season. However, as shown in Table 2, by 1996 most of the catch was more or less evenly distributed throughout the entire fishing season.

Since 1993, temporary quota transfers for a fishing season have been permitted, although limitations remain on how much one vessel can harvest. Each vessel's quota is divided in two equal shares, and any licensed halibut fisher is allowed to fish a maximum of four shares per vessel.[21] The limit on the quota shares per vessel means that the maximum harvest of any one vessel is the sum of the four largest shares in the fleet, or 1.57 percent of the TAC. Permanent transfers of quota have been allowed since 1991 but can only be made to vessels without an existing halibut license and only to vessels that are not more than 10 feet longer than the vessel that is transferring the license. Table 3 provides a record of temporary transfers of quota. Every year since 1993, when temporary transfers were permitted, trading has increased and in 1996 involved 216 vessels and almost half the entire quota.[22] Most trades have been for quantities of quota ranging from 4,400

[20] Bruce R. Turris, personal communications (1997).

[21] Paul MacGillivray, Experience with Individual Vessel Quotas in the British Columbia Halibut Fishery (paper presented at the conference Managing a Wasting Resource: Would Quotas Solve the Problems Facing the West Coast Salmon Fishery? Vancouver, May 30 and 31, 1996).

[22] Turris, *supra* note 20.

TABLE 2

FRACTION OF TOTAL HALIBUT CATCH CAUGHT EACH MONTH: 1991, 1994, AND 1996

	1991	1994	1996
January	N.A.	N.A.	N.A.
February	N.A.	N.A.	N.A.
March	N.A.	.24	.14
April	N.A.	.17	.14
May	.17	.17	.13
June	.31	.06	.12
July	.07	.11	.11
August	.08	.05	.12
September	.1	.06	.11
October	.26	.14	.11
November	N.A.	N.A.	N.A.
December	N.A.	N.A.	N.A.

SOURCE.—Bruce R. Turris, personal communications (1997).

NOTE.—The fleet is allowed to land halibut in the first few days in November and thus the harvest for November is added to October. N.A. refers to months outside of the fishing season. The monthly catch percentages do not sum to 100 due to rounding error.

TABLE 3

TEMPORARY TRANSFERS OF INDIVIDUAL QUOTA IN THE BRITISH COLUMBIA HALIBUT FISHERY

Year	No. of Transfers	No. of Vessels Involved	% of Total Quota
1991	0	0	0
1992	0	0	0
1993	178	94	19
1994	306	154	34
1995	360	184	39
1996	413	216	44

SOURCE.—Bruce R. Turris, personal communications (1997).

to 15,400 pounds and have allowed lower cost fishers to acquire a greater share of the total catch. Despite the change in transferability, under the current TAC, most fishers cannot acquire enough quota to make halibut fishing their sole source of revenue. Thus many halibut license holders are actively engaged in other fisheries including salmon, rockfish, and sablefish.[23]

[23] Casey *et al.*, *supra* note 19.

The introduction of IVQs has led to a number of important changes in the fishery. Transferability of quota reduced the number of active fishing vessels by almost 20 percent from 1991 to 1993 and by a further 11 percent from 1993 to 1994. Despite the transfers, quota is not heavily concentrated by area, individuals, or companies, and most of the active vessels remain owner operated.[24] Individual harvesting rights have also reduced the number of crew employed from around 1,600 in 1990 to 1,300 in 1992, or a drop of almost 20 percent.[25] This trend continued after quota transfers were permitted. The fall in crew size is due to a reduction in demand for large crews that were formerly needed to harvest the catch in the ''derby'' fishery, when the season lasted just a few days, and because some individuals are working on more than one vessel due to the longer fishing season.

The major short-run benefit of IVQs has been the increased fishing season, which has enabled fishers to sell higher quality and fresher fish and may have also increased their market power relative to fish processors.[26] Prior to IVQs, about half the halibut landed was marketed as fresh, while today almost the entire catch is sold as higher priced fresh fish.[27] The price premia, attributable to IVQs, ranged from 22 to 34 percent in the period 1991–94.[28] These premia suggest that IVQs increased total revenues to the halibut fleet by as much as C$23 million in the first 4 years of the program. The increased returns far exceed the extra costs associated with IVQ management, which represented in total less than C$3 million for the period 1991–94. The changes in the fishery have also been accompanied by an increasing price for halibut quota.[29]

In addition to economic changes, IVQs have also led to other benefits in the halibut fishery. In a survey of the fleet in 1994, Keith Casey and coworkers[30] found that 72, 73, and 68 percent of respondents either agreed or strongly agreed that IVQs have made fishing safer, resulted in less loss of fishing gear, and reduced wastage of fish. In an earlier survey of the fleet in 1992, fishers rated ''better safety'' as the single most important benefit of IVQs.[31] According to the DFO, discards of undersized halibut have also

[24] Porter, *supra* note 16.

[25] MacGillivray, *supra* note 21.

[26] H. Alan Love *et al.*, Regulatory Controls and Market Power Exertion: A Study of the Pacific Halibut Industry, 9 Nat. Resource Modeling 229 (1995).

[27] Casey *et al.*, *supra* note 19.

[28] Mark Herrmann, Estimating the Induced Price Increase for Canadian Pacific Halibut with the Introduction of the Individual Vessel Quota Program, 44 Can. J. Agric. Econ. 151 (1996).

[29] Porter, *supra* note 16.

[30] Casey *et al.*, *supra* note 19.

[31] E. B. Economics, Evaluation Study of Individual Quota Management in the Halibut Fishery (1992).

been reduced by half as a result of individual harvesting rights,[32] while incidental catches of other species, such as rockfish, are now landed rather than discarded at sea. A fisher-funded monitoring program also provides greater control over excess and illegal landings, and, for the first time, fishers have voluntarily contributed to ongoing costs of stock assessment undertaken by the IPHC.

IV. Modeling Economic Efficiency

To evaluate the changes brought about by private harvesting rights in the BC halibut fishery, we estimate technical cost, allocative, and overall economic efficiency for each vessel relative to a ''best practice'' frontier isoquant calculated from a stochastic production frontier.[33] Technical efficiency reflects the ability of a firm to produce a given output level with the minimum quantities of inputs. Technical cost efficiency (TE) measures the ratio of the cost of the technically efficient input bundle to the cost of the actual or observed input bundle and captures the cost savings possible from technically efficient production. A production process is allocatively efficient in its input usage when the firm equates ratios of marginal products with the input price ratios to minimize cost given output and input prices. Allocative efficiency (AE) represents the reduction in production costs if production were both technically and allocatively efficient, rather than technically efficient but allocatively inefficient. Economic efficiency (EE) is the capacity of a firm to produce a given quantity of output at minimum cost through both technical and allocative efficiency and is the product of TE and AE.[34]

The efficiency measures in the study are defined by comparing input bundles along a given ray, defined by the observed input proportions, through the origin. Technical and technical cost efficiency are input-oriented measures from the efficient isoquant, rather than directly measured from the estimated best-practice production frontier, an output-oriented measure. The

[32] MacGillivray, *supra* note 21.

[33] This discussion draws upon Boris E. Bravo-Ureta & Laszlo Rieger, Dairy Farm Efficiency Measurement Using Stochastic Frontiers and Neoclassical Duality, 73 Am. J. Agric. Econ. 421 (1991); M. J. Farrell, The Measurement of Production Efficiency, 120 J. Royal Stat. Soc'y, Ser. A, 253 (1957); Raymond J. Kopp, The Measurement of Productive Efficiency: A Reconsideration, 96 Q. J. Econ. 477 (1981); Raymond J. Kopp & W. Erwin Diewert, The Decomposition of Frontier Cost Function Deviations into Measures of Technical and Allocative Efficiency, 19 J. Econometrics 319 (1982); and William H. Greene, The Econometric Approach to Efficiency Analysis, in The Measurement of Productive Efficiency: Techniques and Applications (Harold Fried, C. A. Knox Lovell, & Shelton Schmidt eds. 1993).

[34] Kopp, *supra* note 33.

input- and output-oriented measures are equivalent given constant returns to scale.

Single-factor cost measures of technical and allocative efficiency are also calculated in which all other inputs (both variable and fixed) and output are held at observed levels.[35] Each measure of single-factor efficiency reflects the cost reductions possible through the increase of a single factor's efficiency, rather than the cost saving associated with a proportional increase in the efficiency of *all* inputs. As noted by Raymond Kopp,[36] the single-factor technical cost efficiency measure is functionally related to relative factor prices and is thus not entirely free of allocative effects.[37]

A. Data

The data were obtained from DFO cost and earnings surveys from an independent random sample of 97, 163, and 54 halibut fishers in 1988, 1991, and 1994, respectively, and are neither a panel nor a rotating panel of vessels. A selection of 107 observations (1988, 1991, and 1994 combined) was made from the annual data using the criteria that all vessels used bottom longline gear and caught halibut and their reported revenues matched (within 10 percent) the independently obtained value of halibut landings recorded for each license holder.

For each vessel, home port fuel prices were obtained from Chevron Canada and Imperial Oil Canada. The price of labor was measured as an opportunity cost of labor equal to an expected weekly earnings in manufacturing for each region where the vessels have their home ports. Vessel length and quantity and value of fish landings came from records kept by the DFO. A measure of the exploitable biomass (total weight) of the common-pool resource, which indicates the abundance of the halibut stock, came from Pat-

[35] The single-factor technical cost efficiency measures are calculated from the isocost line associated with the minimum input quantity of each input, given fixed capital and the other variable factor fixed at observed levels, following Kopp, *supra* note 33, at 492. The technically cost efficient input, with other inputs held at their observed levels, was calculated from the corresponding isoquant. They could be equivalently calculated in the same manner as the technically cost efficient inputs for the multiple-factor technical cost efficiency measures, adapting Kopp & Diewert, *supra* note 33; Timothy G. Taylor, H. Evan Drummond, & Aloisio T. Gomes, Agricultural Credit Programs and Production Efficiency: An Analysis of Traditional Farming in Southeastern Minas Gerais, Brazil, 68 Am. J. Agric. Econ. 114 (1986); and Greene, *supra* note 33. The single-factor allocative efficiency measures are calculated following Kopp, *supra* note 33, at 494.

[36] Kopp, *supra* note 33, at 493.

[37] The Appendix and Figure 1 of R. Quentin Grafton, Dale Squires, & Kevin J. Fox, Private Property and Economic Efficiency: A Study of a Common-Pool Resource (Discussion Paper No. 9906, Univ. Otago, Dep't Econ. 1999), provide further details on the interpretation and measurement of efficiency.

rick Sullivan, Ana Parma, and Richard Leickly.[38] All economic values are in C$1994 after inflating 1988 and 1991 values by the gross domestic product implicit price index. Summary statistics of the data are presented in Table 4, where the halibut fleet is defined as all longline vessels that had a plurality of revenue from halibut and the general fleet includes all licensed longline vessels that caught halibut.

B. Stochastic Frontier

Halibut fishers combine labor, capital, and fuel to produce an endogenous product, the catch of halibut.[39] Given an exogenous price for landed halibut and expectations about the availability and abundance of halibut, fishers select and transit to halibut grounds and lay their longline gear to maximize expected profits.

The halibut longline harvesting technology is specified as a stochastic frontier.[40] The frontier is stochastic because fishing is sensitive to random factors such as weather, resource availability, and environmental influences.[41] A common specification for the stochastic frontier is the Cobb-Douglas function. This form was selected in this study because it is self-dual, that is, the cost function can be directly obtained from the production function and vice versa. The Cobb-Douglas function imposes elasticities of substitution equal to one, homogeneity, and strong separability among inputs. Flexible functional forms, which generally relax these restrictive assumptions, are not self-dual. However, self-duality is a necessary property to derive measures of allocative and economic efficiency from the produc-

[38] Patrick J. Sullivan, Ana M. Parma, & Richard C. Leickly, Population Assessment, 1994 Technical Supplement (1994).

[39] Fishers, both before and after the introduction of IVQs, were able to choose their expected harvest quantity of halibut. In the derby fishery, immediately prior to 1991, fishers worked as much as 24 hours a day to catch as many fish as possible in the limited fishing season. Since 1993, fishers have been able to trade quota shares to increase or decrease their scale of operations. In 1991 and 1992, when only transfers of halibut licenses (with attached quota) were allowed, fishers still had the flexibility to land up to 10 percent less or more than their quota, which could be banked or deducted from their quota holdings in the following year. In addition, by their choice of where and when to fish, fishers can adjust their output mix in terms of the quality and size of fish harvested.

[40] The stochastic frontier framework was introduced by Dennis Aigner, C. A. Knox Lovell, & Peter Schmidt, Formulation and Estimation of Stochastic Frontier Production Function Models, 6 J. Econometrics 21 (1977). Their model was extended by Peter Schmidt & C. A. Knox Lovell, Estimating Technical and Allocative Inefficiency Relative to Stochastic Production and Cost Frontiers, 9 J. Econometrics 343 (1979), to incorporate allocative inefficiency.

[41] James E. Kirkley, Dale Squires, & Ivar E. Strand, Jr., Assessing Technical Efficiency in Commercial Fisheries: The Mid-Atlantic Sea Scallop Fishery, 77 Am. J. Agric. Econ. 686 (1995).

TABLE 4

SUMMARY STATISTICS OF THE DATA

VARIABLE	HALIBUT FLEET Mean	HALIBUT FLEET SD	GENERAL FLEET Mean	GENERAL FLEET SD
1988, 1991, and 1994 halibut data:				
Vessel length (meters)	12.65	2.78	14.10	5.45
Crew-weeks	10.08	6.70	12.91	9.68
Fuel quantity (liters)	4,955.01	5,212.75	6,995.15	9,505.11
Halibut revenue	66,104.92	50,084.16	88,747.81	70,140.23
Price of halibut	2.81	.60	2.78	.72
Halibut landings (pounds)	25,090.42	20,132.90	34,026.63	28,966.98
Crew	3.25	1.32	3.78	1.48
Weeks fished	3.11	1.65	3.36	1.92
Landings/crew	7,245.96	4,312.38	8,143.52	4,561.69
Landings/week	8,995.51	7,704.21	11,731.65	9,798.18
Fuel cost	1,616.09	1,740.24	2,420.62	3,634.45
Labor cost	1,816.83	655.43	2,081.87	740.22
No. of observations	36		107	
1988 halibut data:				
Vessel length (meters)	14.01	2.79	14.48	3.54
Crew-weeks	13.64	6.31	15.68	11.33
Fuel quantity (liters)	4,951.96	3,682.49	8,303.381	3,201.26
Revenue	91,397.09	55,032.15	107,329.48	74,208.75
Price	2.03	.14	2.03	.15
Halibut landings (pounds)	44,506.27	24,560.20	51,769.55	33,978.76
Crew	4.09	1.25	4.52	1.55
Weeks fished	3.36	1.29	3.39	1.97
Landings/crew	10,880.00	4,088.18	10,735.89	4,863.64
Landings/week	15,489.24	10,148.10	17,541.05	11,388.93
Fuel cost	1,954.27	1,086.63	3,257.05	5,137.61
Labor cost	2,131.14	714.44	2,346.55	767.18
No. of observations	11		44	
1991 halibut data:				
Vessel length (meters)	12.04	2.59	13.44	7.34
Crew-weeks	7.86	5.10	8.57	5.39
Fuel quantity (liters)	3,609.77	2,545.11	4,153.69	2,767.51
Revenue	42,170.29	29,688.79	51,378.07	34,241.58
Price	3.04	.23	3.08	.21
Halibut landings (pounds)	13,576.86	8,901.37	16,475.10	10,690.77
Crew	2.90	1.18	3.02	1.09
Weeks fished	2.71	1.65	2.91	1.79
Landings/crew	4,563.57	1,580.80	5,224.56	1,972.49
Landings/week	5,894.90	4,645.41	7,199.40	5,809.97
Fuel cost	998.21	725.82	1,122.86	710.79
Labor cost	1,681.71	637.43	1,745.87	590.17
No. of observations	21		44	
1994 halibut of data:				
Vessel length (meters)	12.13	1.63	14.73	3.77
Crew-weeks	12.00	2.45	16.53	9.85
Fuel quantity (liters)	12,025.94	8,699.39	10,545.78	7,758.94
Revenue	122,208.25	67,848.68	132,257.05	82,213.02
Price	3.72	.29	3.85	.30
Halibut landings (pounds)	32,413.00	17,014.47	33,583.47	19,681.81
Crew	2.75	1.27	3.79	1.28
Weeks fished	4.50	2.15	4.37	1.74
Landings/crew	11,334.92	4,133.23	8,682.33	4,283.86
Landings/week	7,416.02	4,143.12	8,653.84	6,131.51
Fuel cost	3,930.00	4,201.54	3,488.95	2,548.30
Labor cost	1,660.80	282.30	2,247.05	715.96
No. of observations	4		19	

NOTE.—All values are in C$1994 and are per vessel. Crew size includes captain. Weeks fished pertains to weeks actively fishing halibut. Halibut landings are in pounds and the price is per pound. Fuel quantity is in liters, and vessel length is in meters. Halibut fleet is defined as longline vessels that had a plurality of revenue from halibut.

tion frontier (primal), in which there is an internally consistent and exact relationship between the allocative inefficiency in factor demands and in the associated cost function.[42]

To calculate the different measures of cost efficiency from the production frontier, the output level of each vessel is set at the observed quantities allowing for stochastic noise. The stochastic production frontier presupposes endogenous output and requires the behavioral objective of expected profit maximization. Measuring allocative inefficiency directly from a (minimum) cost function, whether a self-dual or flexible functional form, presupposes an exogenous output and cost minimization.

The Cobb-Douglas stochastic production frontier is specified as[43]

$$\ln H = \alpha_0 + \alpha_1 \ln K + \alpha_2 \ln L + \alpha_3 \ln F + \alpha_4 \ln B + \varepsilon, \qquad (1)$$

where H denotes a vessel's halibut catch in pounds; K is a vessel's hull length in centimeters and is a measure of the capital stock; L is the flow of labor services for halibut fishing, defined as the number of crew (including the captain) who fished for halibut multiplied by the number of weeks spent halibut fishing; F denotes fuel consumption in liters; and B is the exploitable halibut biomass in 10 million pounds. The biomass variable serves as a technological constraint in this stock-flow production technology. Fuel consumption is implicitly defined as the total cost of fuel divided by the price of fuel.

The error term ε is composed of two independent components and is defined as $\varepsilon = V - U$. The V is a two-sided error term that captures random shocks and is assumed to be symmetrical and independently and identically distributed as $N(0, \sigma_V^2)$. The nonnegative one-sided error term U captures differences in technical efficiency and is assumed to be distributed half-normal.[44] Given that we do not have a panel data set, technical inefficiency for each vessel is defined as the expected value of U conditional on the value of ε, that is, $E[U|\varepsilon]$.[45]

[42] A minimum cost frontier presupposes that output is fixed, which was not the case in 1988, prior to the introduction of IVQs, or in 1994 after the property right was made transferable. Subal Kumbhakar, Modeling Allocative Efficiency in a Translog Cost Function and Cost Share Equations: An Exact Relationship, 76 J. Econometrics 351 (1997), recently modeled an exact relationship for allocative efficiency for the minimum cost frontier, but this solution to ''the Greene problem'' requires cost minimization with an exogenous output. Following Schmidt & Lovell, *supra* note 40, Kumbhakar derived the exact relationship between allocative inefficiency in the share equations (factor demand equations) and in the cost function for a translog functional form.

[43] The Cobb-Douglas minimum cost function and factor demands are given in equations (3) and (4) of Schmidt & Lovell, *supra* note 40, and equation (2) of Taylor, Drummond, & Gomes, *supra* note 35.

[44] Aigner, Lovell, & Schmidt, *supra* note 40.

[45] James Jondrow *et al.*, On the Estimation of Technical Inefficiency in the Stochastic Frontier Production Function Model, 19 J. Econometrics 233 (1982). Given the overwhelm-

The vessel or capital is unlikely to be fully variable in any given time period and hence can be considered as quasi-fixed rather than as a variable input when measuring efficiency. Several factors contribute to this quasi-fixity: (1) the vessel is lumpy and difficult to adjust over short time periods, (2) halibut fishers use their vessels in other fisheries where DFO imposes restrictions on length and size, and (3) persons purchasing halibut quota and a license cannot use the license on a vessel that is more than 10 feet longer than the vessel where it was previously used. Thus, with the exception of the long-run technical primal and cost efficiency measures, all estimates of efficiency are calculated treating the actual vessel length as a quasi-fixed factor.

Short-run efficiency measures can be calculated from the short-run Cobb-Douglas minimum cost frontier, which is self-dual to the short-run Cobb-Douglas stochastic production frontier.[46] The short-run frontier is formed by fixing K at the observed levels, and the short-run cost efficiency measures are calculated conditional upon the output level from the production frontier, accounting for stochastic noise.[47] The efficiency scores fall between zero and one, where a score of one indicates that the fishers produce at the best practice frontier.

C. Measuring Efficiency

To evaluate the effects of private harvesting rights on the different measures of short-run efficiency, efficiency scores from the minimum short-run cost frontier were used to test for the effects of year and vessel-size class dummy variables in Tobit regressions.[48] This approach to measuring

ing importance of ''captain's skill'' in locating and catching fish and the inherent stochastic effects from weather, temperature, and biological variations in fishing, it is likely that technical inefficiency is more unforseen than expected. Thus we specify the technical inefficiency as unexpected or unforseen. If technical inefficiency is unexpected, we can use the expected profit maximization argument of A. Zellner, J. Kmenta, & J. Dreze, Specification and Estimation of Cobb-Douglas Production Function Models, 34 Econometrica 784 (1966), to treat inputs as exogenous. See Peter Schmidt, Frontier Production Functions, 4 Econometric Rev. 289 (1985); and Subal Kumbhakar, The Specification of Technical and Allocative Inefficiency in Stochastic Production and Profit Frontiers, 34 J. Econometrics 336 (1987).

[46] We are grateful for discussions with Knox Lovell and Rolf Färe about the appropriate specification of the frontier to measure short-run changes in technical and allocative efficiency.

[47] If the production function is homogeneous of degree r, then the inefficiency term estimated from a cost function is $1/r$ times the counterpart from the production function (Greene, *supra* note 33, at 89). This accounts for the scale economy effects associated with cost efficiency. Stochastic noise is accounted for in a manner described by Bravo-Ureta & Rieger, *supra* note 33.

[48] Incorporating these dummy variables in the stochastic frontier is not appropriate as the effect of privatizing the fishery would already be incorporated in the efficiency scores of the ''first-stage.'' An alternative method is to simultaneously estimate the stochastic frontier and technical inefficiency equation (George Battese & Tim J. Coelli, A Model for Technical Inefficiency Effects in a Stochastic Frontier Production Function for Panel Data, 20 Empirical

changes in efficiency tests the significance of the annual dummy variables for 1988 (D_{88}), 1991 (D_{91}), and 1994 (D_{94}), multiplied by dummy variables for two size classes of vessels: small, or less than 50 feet (D_S), and large, equal to or greater than 50 feet (D_L).

Potentially different effects in efficiency due to vessel size may arise due to a number of factors. First, a lack of transferability of quota in 1991 and 1992, coupled with an initial quota allocation that penalized smaller vessels relative to larger vessels, may have led to a differential effect on efficiency depending on vessel size. Since 1993, transfers of quota have been allowed, but larger vessels are more affected than small vessels by concentration limits on quota that prevent fishers from fully adjusting their scale of operation. Second, the largest vessels, which employ more crew and greater quantities of fuel, may have greater flexibility in their production process to substitute between these inputs and thereby improve allocative efficiency.

The Tobit regressions account for the censoring of the technical, allocative, and economic efficiency measures at zero and one. The effects of ''privatizing the fishery'' are evaluated by Wald tests of the null hypothesis of no change in efficiency between two time periods (1988–91, 1991–94, and 1988–94) for a given vessel size class (large and small). Thus, $D_{88}D_S - D_{91}D_S = 0$ tests the null hypothesis of equal efficiency for small vessels between 1988 and 1991. If the chi-square value is significant for an efficiency measure (given a single linear restriction and hence one degree of freedom), then the null hypothesis of equal efficiency is rejected.[49]

The tests of changes in efficiency assume no technical change over the period 1988–94. Such an assumption is not unreasonable because, in fishing, the technology is embedded in either the vessel or the gear. Further, in the halibut fishery all vessels in the sample were built prior to 1988, while the harvesting gear that can be used by fishers is strictly regulated.[50]

Econ. 325 (1995)). The ''one-stage'' estimation procedure is inappropriate in the halibut fishery because we fix capital (vessel size) and then calculate short-run cost efficiency measures accounting for the short-run economies of scale. Moreover, we also evaluate the relationship between short-run allocative cost efficiency, overall cost efficiency, and single-factor technical and allocative cost efficiency and the dummy variables for vessel size class and years. It is unclear what the effect would be on these short-run efficiency measures and the Tobit regressions if the long-run stochastic production frontier and ''long-run'' technical inefficiency were estimated simultaneously in a one-stage routine. Finally, gains in econometric efficiency for the second-stage regressions were not possible from Tobit regressions in a system of equations, estimated by the method of Zellner's seemingly unrelated regressions, because the regressors in all of the cost efficiency equations were identical and there were no cross-equation constraints.

[49] This approach gives a two-way analysis of variance, accounting for the censoring of the efficiency scores. Estimated regression coefficients are mean values of the efficiency scores for the given category. Standard errors give the within group variation for each category.

[50] Incorporating time-varying technical change into technical efficiency effects also requires restrictive assumptions about the nature of the technical change and would be inappro-

TABLE 5

PARAMETER ESTIMATES OF THE STOCHASTIC PRODUCTION FRONTIER

Variable	Value	SE
Constant	2.2436	1.4287
Vessel length	1.0294*	.2221
Labor	.4122*	.1175
Fuel	.2769*	.0781
Biomass	1.0281*	.3508
Log-likelihood	−90.7885	
No. of observations	107	
σ_V^2	.10056	
σ_U^2	.65863	
$\lambda = \sigma_U/\sigma_V$	2.5593*	1.2394
$\sigma_V + \sigma_U$	1.1287*	.1080
$\sigma_V^2 + \sigma_U^2$	.7592*	.2441
$\gamma = \sigma_U^2/(\sigma_V^2 + \sigma_U^2)$	.8675*	.1464

NOTE.—Dependent variable is halibut catch in pounds. Vessel length is in meters, fuel is in hundreds of liters, and biomass is in 10 million pounds. The model was estimated under the assumption that the technical inefficiency error term (U) is distributed half-normal. A likelihood ratio test was performed to test the null hypothesis of no technical efficiency effects, that is, H_0: $\gamma = 0$. The calculated likelihood ratio of 3.555 exceeds the critical χ^2 of 2.71 at the 5% level of significance, and thus the null hypothesis is rejected in favor of the alternative hypothesis, that is, H_1: $\gamma > 0$.

* Statistically significant at the 5% level.

V. EMPIRICAL RESULTS

The stochastic frontier was estimated by maximum likelihood under the behavioral hypothesis that fishers maximize expected profits.[51] Parameter estimates are reported in Table 5 for the 107 observations obtained from the sample data. All parameters are significant at the 5 percent level with the exception of the intercept term. The ratios $\lambda = \sigma_U/\sigma_V$ and $\gamma = \sigma_U^2/\sigma_V^2 + \sigma_u^2$ provide measures of model performance. The ratio λ is greater than one and is statistically significant, and γ is statistically significant, which implies that technical inefficiency effects exist in the data and that they account for more of the variability than random factors.[52]

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priate given that short-run cost efficiency measures are based on observed vessel size. A time trend in the stochastic frontier would also capture the changes in privatization, and not just technical change, which would bias the results in the Tobit regressions.

[51] Zellner, Kmeta, & Dreze, *supra* note 45.

[52] A likelihood ratio (LR) tests the null hypothesis of no technical efficiency effects, i.e., H_0: $\gamma = 0$ versus H_1: $\gamma > 0$. Any generalized likelihood ratio statistic associated with a null hypothesis involving the γ parameter has a mixed chi-square distribution because the restriction defines a point on the boundary of the parameter space (Tim Coelli, D. S. Prasado Rao, & George E. Battese, An Introduction to Efficiency and Productivity Analysis

TABLE 6

OVERALL EFFICIENCY SCORES AND PRODUCER SURPLUS MEASURES: 1988, 1991, AND 1994

Efficiency Scores	Mean	SD	Minimum	Maximum
Technical efficiency (primal)	.56	.19	.07	.87
Long-run technical cost efficiency	.70	.15	.22	.92
Short-run technical cost efficiency	.14	.10	.01	.47
Short-run economic efficiency	.12	.09	.01	.42
Short-run allocative efficiency	.88	.10	.46	.99
Fuel techical cost efficiency	.78	.12	.31	.97
Labor technical cost efficiency	.26	.13	.03	.76
Fuel allocative efficiency	.17	.14	.01	.75
Labor allocative efficiency	.46	.27	.05	.99
Producer surplus measures:				
Total producer surplus	79,206	65,723	−25,179	305,999
Total producer surplus (efficient)	87,595	69,089	11,865	343,221
Producer surplus/pound	2.35	.98	−5.00	4.31
Producer surplus (efficient)/pound	2.75	.72	1.73	4.46

NOTE.—Number of observations equals 107. Producer surplus is measured in C$1994.

The exponents for capital, labor, and fuel of the estimated frontier sum to greater than one (biomass is not included in the scale measures because it is a technological constraint beyond the control of individual vessels), indicating increasing returns to scale and, hence, decreasing long-run average costs. Increasing returns to scale with capital variable in the production frontier reflect the cost savings available to firms if they could freely adjust their vessel sizes. Such adjustments in capital, however, are not possible because of restrictions on vessel size in other fisheries in which halibut fishers participate.

A. Short-Run Efficiency Measures

The short-run efficiency measures (where K is fixed at the observed levels) for the general fleet, over all three periods for all vessels and for small and large vessels, are provided in Table 6. Table 7 indicates that the hypothesis that privatization resulted in the same changes in efficiency for small and large vessels could not be rejected. Further, no significant differences in the individual efficiency measures were found between vessels that received a plurality of their revenues from halibut (halibut fleet) and those

(1998)). The critical values are given in Table 1 of David A. Kodde & Franz C. Palm, Wald Criteria for Jointly Testing Equality and Inequality Restrictions, 54 Econometrica 1243 (1986). If the test statistic is distributed as a chi-square random variable with 1 degree of freedom and the LR statistic exceeds the critical value of 2.71, the null hypothesis is rejected in favor of the alternative hypothesis at the 5 percent level of significance. For the model in question the test statistic was 3.555, and thus the null of no technical efficiency effects is rejected.

TABLE 7

TESTS OF SIGNIFICANCE WHETHER VESSELS ARE IDENTICAL IN EVERY PERIOD

	H_0: SMALL VESSELS = LARGE VESSELS			H_0: HALIBUT FLEET = GENERAL FLEET			H_0: CORE VESSELS = NONCORE VESSELS		
EFFICIENCY	χ^2	Significance	Reject (Y/N)	χ^2	Significance	Reject (Y/N)	χ^2	Significance	Reject (Y/N)
Technical efficiency (primal)	.32	.95594	N	2.24	.52465	N	1.07	.78471	N
Long-run technical efficiency (cost)	.39	.94139	N	1.93	.58697	N	.84	.83990	N
Short-run technical efficiency (cost)	.71	.87161	N	4.91	.17849	N	1.75	.62639	N
Short-run economic efficiency	.16	.98376	N	4.21	.24012	N	1.32	.72395	N
Short-run allocative efficiency	1.17	.76082	N	1.05	.78798	N	4.87	.18152	N
Single-factor fuel technical efficiency	.76	.85991	N	1.45	.69410	N	2.44	.48611	N
Single-factor labor technical efficiency	.22	.97433	N	2.66	.44755	N	2.70	.43975	N
Single-factor fuel allocative efficiency	.20	.97695	N	3.26	.35318	N	1.59	.66128	N
Single-factor labor allocative efficiency	1.05	.78841	N	3.35	.34053	N	1.03	.79386	N
Unit quota rent	20.96	.00011	Y	4.04	.25758	N	6.69	.08251	N
Total observed producer surplus	47.18	.0	Y	1.95	.58375	N	1.85	.60502	N
Total efficient producer surplus	50.36	.0	Y	3.83	.28099	N	1.81	.61201	N
Observed producer surplus per pound	3.66	.29995	N	1.07	.78471	N	1.03	.79306	N
Efficient producer surplus per pound	20.00	.00017	Y	.84	.83990	N	6.69	.08242	N

NOTE.—Hypothesis tests are all Wald tests with 3 degrees of freedom at the 5% level of significance. Core vessels are boats for which data are available in two out of the three sample periods. Noncore vessels are boats for which data are available in only one of the three sample periods.

that did not (general fleet) or between vessels that were in more than one sample period (core vessels) or not (noncore vessels). A reason why the relative specialization in halibut may not affect changes in efficiency across the fleet is that, regardless of their revenue received from halibut, fishers only target halibut when fishing for halibut. Thus whether a vessel receives a plurality of revenue from halibut or not, fishers have the same incentives to optimize the use of the variable inputs when fishing for halibut.

The efficiency scores over all 3 years indicate substantial scope to improve most measures of efficiency. For all vessels and over all 3 years, mean short-run allocative efficiency is .88, but mean short-run technical cost efficiency is .14, giving a low mean short-run economic efficiency of .12. Thus given their observed output and fixed capital stock, vessels are allocating variable inputs as a group relatively well at the margin but are extremely inefficient in terms of technical cost efficiency. The results suggest that improvements in the use of all variable inputs would significantly reduce harvesting costs.

Table 8 summarizes the results of the significance tests about changes in efficiency over time and across vessel size classes.[53] The results indicate that short-run technical and economic cost efficiency declined significantly, at the 5 percent level, between 1988 and 1991 for both vessel classes. Short-run allocative cost efficiency also declined for both small and large vessels over the period 1988–91, but not significantly. By contrast, all the multifactor changes in short-run cost efficiency for both small and large vessels were positive between 1991 and 1994. At the 5 percent level of significance, however, the only significant multifactor short-run change for large vessels over the 1991–94 period was economic cost efficiency, while for small vessels the only significant change was short-run technical cost efficiency. Over the period 1988–94, there were no changes of significance in any measures of efficiency for small or large vessels, and the change over each period for each measure of efficiency was identical for both small and large vessels. Explanations for the changes in short-run, single-factor, and long-run efficiency are explored in Section VI.

B. Single-Factor Efficiency

Single-factor efficiency measures allow us to isolate the most important sources of short-run technical cost and allocative inefficiency. Table 8 indicates that the changes in labor and fuel technical and allocative cost effi-

[53] The results of the Tobit regressions and the tests of significance are found in Grafton, Squires, & Fox, *supra* note 37, and are also available from the authors upon request.

TABLE 8

Direction and Significance of Efficiency Changes over Time by Vessel Size Class: General Fleet

Efficiency	Small Vessels 1988–91	Small Vessels 1991–94	Small Vessels 1988–94	Large Vessels 1988–91	Large Vessels 1991–94	Large Vessels 1988–94
Technical efficiency (primal)	−*	+*	−	−*	+	−
Long-run technical efficiency (cost)	−*	+*	−	−*	+	−
Short-run technical efficiency (cost)	−*	+*	−	−*	+	−
Short-run economic efficiency	−*	+	−	−*	+*	−
Short-run allocative efficiency	−	+	+	−	+	+
Single-factor fuel technical efficiency	+	−	−	+	−	−
Single-factor labor technical efficiency	−*	+*	−	−*	+	−
Single-factor fuel allocative efficiency	−*	+*	−	−*	+	−
Single-factor labor allocative efficiency	−*	+	−	−	+	−
Unit quota rent	+*	+*	+*	+*	+*	+*
Total observed producer surplus	−*	+*	+	−*	+*	+*
Total efficient producer surplus	−*	+*	+	−*	+*	+*
Observed producer surplus per pound	+*	+*	+*	+*	+*	+*
Efficient producer surplus per pound	+*	+*	+*	+*	+*	+*

Note.—The symbol + (−) indicates positive (negative) change in the efficiency measure.
* Statistically significant at the 5% level.

ciency are the same sign for both small and large vessels between 1988–91, 1991–94, and 1988–94.

The overall efficiency scores in Table 6 indicate that labor use contributes the most to short-run technical cost inefficiency, given a fixed vessel size. The low technical cost inefficiency for labor is explained by the ''derby'' fishing, practiced before the introduction of private harvesting rights in 1991, which placed a premium on the most rapid possible harvesting of fish. Table 8 shows that labor technical cost efficiency significantly fell between 1988 and 1991 for both small and large vessels but significantly increased for small vessels between 1991 and 1994. A possible explanation for the decline in labor technical cost efficiency between 1988 and 1991 is that captains failed to adjust crew sizes sufficiently in the first year of IVQs. The absence of significant gains in labor technical cost efficiency from 1988 to 1994, for both small and large vessels, may also be a result of changes in hours worked per day by crew, which is not captured in the data. For instance, before the introduction of IVQs in 1991, crews often worked 24 hours per day while after privatization crews rarely work more than 12 hours per day.

Table 6 also indicates that over all 3 periods fuel provides the greatest source of single-factor allocative inefficiency. As with the use of labor, under a ''derby'' fishery vessel owners tried to maximize their harvests in the shortest period of time and paid little heed to conserving fuel or using it in the correct proportion with labor to minimize costs. Table 8, however, indicates that there was a significant and negative change in fuel allocative efficiency from 1988 to 1991, for both small and large vessels, but a significant improvement in this efficiency measure for small vessels between 1991 and 1994. There were, however, no significant changes at the 5 percent level in any of the single-factor efficiency measures for either vessel size class from 1988 to 1994.

C. Long-Run Efficiency

Long-run efficiency measures are calculated assuming that fishers can freely adjust their vessel size. Table 6 shows that the average long-run technical cost efficiency score for all vessels would increase fivefold from 0.14 to 0.70 if fishers were able to freely adjust their vessel size.[54] This suggests

[54] The technical inefficiency term from the stochastic production frontier is adapted for cost efficiency by dividing by the production frontier's degree of economies of scale (Schmidt & Lovell, *supra* note 40; Greene, *supra* note 33, at 89). Similarly, the estimated inefficiency obtained in the context of a cost function can be translated into a Farrell measure of technical inefficiency by multiplying it by the degree of homogeneity of the production function, r, as per equation (4) of Schmidt & Lovell, *supra* note 40. The inefficiency measure from a Cobb-Douglas production function can be multiplied by $1/r$ and then converted to a

that, in the long run, some of the largest potential gains in cost efficiency may come from choosing the desired vessel size.

Unfortunately, fishers are currently prevented from choosing their vessel size because of restrictions in vessel licenses that are distinct from regulations governing IVQs. For instance, most of the halibut fleet participate in other fisheries (such as salmon), which are regulated by vessel licenses, input controls, and limits on vessel size. In addition, fishing licenses are ''bundled'' by vessel, so that fishers wishing to increase the size of their vessel must find a willing seller who has the same combination of licenses and who owns a larger vessel. Finding the desired match of buyer and seller is difficult and costly, and may even be impossible, depending upon the combination of fishing licenses and vessel size desired. Thus, without flexibility in the choice of vessel size by fishers, the potential gains in long-run cost efficiency will not be realized.

D. Producer Welfare: Producer Surplus and Unit Quota Rent

A potential gain from the use of IVQs is an increase in revenues and rents due to an improvement in quality and change in product form. One measure of the potential change is the unit rent of quota, defined as the output price less the virtual price, where the virtual price is the marginal opportunity cost of production of a quota when there is a single output.[55] Where fishers are able to adjust their scale of operation at the margin, the unit quota rent per pound represents the return from owning an additional pound of quota and should approximate its annual lease price.

In the BC halibut fishery, the average unit quota rent from the 19 vessels in the sample in 1994 was $3.84 per pound. By contrast, the average lease price of quota in 1994 was $2.00 per pound. The difference between potential and actual unit quota rents may be explained by the restrictions imposed on quota transfers. For instance, temporary transfers, which have been permitted since 1993, are allowed only in blocks of quota (in quantities usually not less than 4,400 pounds) equal to one-half of the original quota allocation per vessel. Concentration restrictions also prevent any one vessel from using more than four blocks of quota. In turn, these restrictions may have

technical cost efficiency measure by the approach of George Battese & Tim J. Coelli, Prediction of Firm-Level Technical Efficiencies with a Generalized Frontier Production Function and Panel Data, 38 J. Econometrics 387 (1988). Thus, to estimate long-run technical *cost* efficiency, the firm-level technical inefficiency measures from the estimated production frontier are adjusted by the long-run measure of homogeneity, the sum of the production coefficients for labor services (*L*), fuel consumption (*F*), and capital (*K*) in equation (1).

[55] Dale Squires & James E. Kirkley, Resource Rents from Single and Multispecies ITQ Programs, 52 ICES J. Marine Sci. 153 (1995).

prevented fishers from reaching an optimal scale of operation and reduced the quota rent in the fishery.[56]

Unit quota rents increased significantly between 1988 and 1991, and again from 1991 to 1994, for both small and large vessels. This indicates that the privatization of the fishery provided immediate gains to fishers in terms of an increase in the returns per pound of fish landed in the first year that IVQs were introduced. Moreover, 3 years after the introduction of IVQs, fishers were able to make further improvements in the quality of their landed product and the price received for halibut.

Another way to measure changes in the net revenues of fishers is to calculate the producer surplus per vessel and per pound in 1988, 1991, and 1994. Producer surplus is defined as vessel total revenue less observed variable costs, and efficient producer surplus is defined as vessel total revenue less the economically efficient variable costs.[57] Table 8 indicates that for both small and large vessels, total observed and efficient producer surplus fell significantly between 1988 and 1991, while observed and efficient producer surplus per pound increased significantly over the same period and for the periods 1991–94 and 1988–94. The apparent contradiction between changes in total and per-pound producer surplus for 1988–91 is explained by a 44 percent fall in the TAC over the period between 1988 and 1991, which led to a fall in the total producer surplus as fewer fish were caught. From 1991 to 1994, and for the entire period from 1988 to 1994, observed and efficient producer surplus in total and per pound increased significantly for large vessels, and, over both periods, observed and efficient producer surplus per pound rose significantly for small vessels.

The changes in unit quota rents and producer surplus suggest that one of the principal benefits from privatization has been the increase in total revenue due to higher prices paid for fresher and better-quality fish, caught and

[56] The optimal scale of operation is often measured by scale efficiency using a marginal cost definition with economically efficient marginal cost (Finn Førsund, C. A. Knox Lovell, & Peter Schmidt, A Survey of Frontier Production Functions and of their Relationship to Efficiency Measurements, 13 J. Econometrics 5 (1980)), where a firm is scale efficient if its output price equals economically efficient marginal cost. In a fishery with fully transferable and divisible private harvesting rights, a profit maximizing fisher should, in each time period, set the supply so that the output price equals the marginal harvesting cost plus the lease price of the harvesting right (R. Quentin Grafton, Rent Capture in a Rights-Based Fishery, 28 J. Envtl. Econ. and Mgmt. 48 (1995)). If the property right is not fully divisible, however, fishers are unable to adjust their production at the margin and ''fine-tune'' their operations to be scale efficient.

[57] The economically efficient short-run costs were obtained using the factor demands as defined by Kopp & Diewert, *supra* note 33, and Taylor, Drummond, & Gomes, *supra* note 35. Although the efficient producer surplus and unit quota rents are calculated differently, they provide very similar results.

delivered over most of the year.[58] Such a result confirms predictions that immediate rent gains are likely to emerge on the revenue side from ITQs as a result of new marketing opportunities that arise from the removal of restrictive regulatory structures.[59] The improvement in the product form and quality of fish landed is itself directly attributable to IVQs, which have enabled the regulator to increase the length of the fishing season from 14 days in 1988 to 245 days in 1994.

VI. Explaining Changes in Efficiency

In a ''derby'' fishery, fishers are obliged to catch their harvest in a very limited period, and the costs they incur (with the exception of labor, which is paid a share of the net revenue) may not vary a great deal in terms of the amount of fish caught. For example, at the same engine speed, the amount of fuel used is the same going to and from a fishing ground irrespective of the amount of fish caught. Thus, after the decision has been made to catch fish, the overriding incentive is to catch as many fish as possible, and considerations of costs or cost-minimizing input allocations are of secondary importance.

By contrast, with private harvesting rights the harvest is fixed by the amount of quota owned or leased by fishers. Thus, if the season length is no longer a constraint, the primary economic consideration of fishers is to receive the highest value as possible from the quota and to minimize costs for a given level of harvest. As a result, we would expect that with privatization fishers would adjust the level of all their inputs (technical efficiency) and the mix of inputs (allocative efficiency) to improve overall economic efficiency.

A. Efficiency Changes: 1988–91

Evidence exists that short-run technical and economic efficiency fell over the period 1988–91 for small and large vessels. The decline in efficiency may have arisen from the difficulties associated with the close to 50 percent decline in the 1991 total catch relative to 1988 and because of severe autumn storms in 1991. A lack of efficiency gains between 1988 and 1991 may also have arisen from a ''learning curve'' from an increased fishing season that required fishers to discover where the fish were located at times when they previously had never caught halibut. This effect may help ex-

[58] Casey *et al., supra* note 19, in their study of the BC halibut fishery also observed that the principal benefits of ITQs were in terms of the revenues rather than the costs of fishers.

[59] Frances R. Homans & James E. Wilen, A Model of Regulated Open Access Resource Use, 32 J. Envtl. Econ. & Mgmt. 1 (1997).

plain why in a 1992 survey of halibut fishers most respondents did not record that the use of fuel changed in 1991[60] and why over 30 percent of the total catch was harvested in just 1 month in 1991, but by 1996 no more than 14 percent of the total catch was caught in any 1 month.

B. *Efficiency Changes: 1991–94*

Given that most fishers were near the best practice in terms of allocative efficiency, the biggest proportional gains in short-run cost efficiency in the halibut fishery may be expected in terms of short-run technical cost efficiency. Moreover, given that average short-run labor technical efficiency was much less than short-run technical fuel efficiency, the biggest gains in single-factor technical efficiency from privatization might be expected in the use of labor. The results in Table 8 indicate that, at least for small vessels, short-run technical cost efficiency and short-run labor technical cost efficiency did significantly increase over the period 1991–94.[61]

C. *Attenuated Property Rights*

An explanation for why there were no improvements in efficiency in 1991, but short-run efficiency gains in the period 1991–94, is that the property right was initially limited to a 2-year trial period and was neither transferable nor divisible in 1991 and 1992. As a result, fishers could not trade their quota to reach a desired scale of operation in the first 2 years after IVQs were introduced and, thus, were hindered in their efforts to appropriately set input levels to desired output. Further, uncertainty about whether the property right would continue past 1993 may have persuaded some skippers to retain redundant but competent crew so as to ensure that capable crew would be available, should the property right scheme be discontinued at the end of the trial period.

After temporary transfers of quota were permitted in 1993, trading of quota has been active with 19 and 34 percent of the total quota changing hands in 1993 and 1994. In addition, the number of active vessels in the fishery fell by 28 percent from 433 in 1991 to 313 in 1994. These transfers

[60] E. B. Economics, *supra* note 31.

[61] If a higher level of significance of 20 percent instead of 5 percent is used, such that the probability of rejecting the null hypothesis of *no* change in efficiency is 20 percent when the null is true, then all the short-run measures of cost efficiency are significant for small vessels, with the exception of short-run allocative efficiency. In other words, substantive evidence (Donald N. McCloskey, The Rhetoric of Economics (1985); Thomas Mayer, Truth versus Precision in Economics (1993)) exists that both short-run technical and economic efficiency increased between 1991 and 1994 for both vessel classes.

have, in turn, helped fishers to adjust their scale of operations and make better use of inputs and so improve technical and economic efficiency.

It is not possible to quantify the effects of restrictions of the property right in 1991 and 1992 on efficiency. However, the potential losses associated with limitations in the property rights in terms of the total rents in the fishery can be calculated for 1991 using a nonlinear, price (IVQ)-endogenous mathematical programming model which embeds the estimated harvesting technology and cost structure.[62] The results indicate that if the property right had been transferable in 1991, the producer surplus would have been 4.12 percent higher and would have resulted in a very different outcome in terms of the distribution of the harvest among fishers.[63]

VII. Property Rights and Common-Pool Resources

The use of individual harvesting rights in the BC halibut fishery is just one of many examples of how a change in property rights, or an improvement in the characteristics of property rights, may improve the returns from common-pool resources. For instance, for some years, the United States has been in dispute with several countries over import restrictions of tuna caught in association with dolphins. In an attempt to overcome the dispute and reduce the number of dolphins killed when catching tuna, an agreement (called the Panama Accord) was reached between the 10 nations that catch yellowfin tuna in the eastern tropical Pacific and with environmental and animal rights groups. The Panama Accord's aim is to progressively reduce dolphin mortality and specifies annual dolphin mortality limits (DMLs) for each country, which, in turn, are allocated to each nation's vessels. Vessels that remain under their annual DML may fish for tuna all year, while those vessels which reach their DML must stop tuna fishing.[64] However, if DMLs were divisible, transferable, and longer in duration than 1 year, vessels that were previously constrained by the regulations could continue to fish for

[62] See Squires & Kirkley, *supra* note 55, for a further discussion on price endogenous mathematical programming with IVQs.

[63] The relatively small gains from allowing transfers is explained by the small differences in the virtual prices of the 44 vessels in the 1991 sample. Randal R. Rucker, Walter N. Thurman, & Daniel A. Sumner, Restricting the Market for Quota: An Analysis of Tobacco Production Rights with Corroboration from Congressional Testimony, 103 J. Pol. Econ. 142 (1995), in an analysis of the U.S. flue-cured tobacco industry also found that allowing intercounty trades of tobacco quota only led to small changes in overall producer surplus between .6 and 3.8 percent over the period 1977–86. Nevertheless, they find allowing intercounty transfers would have an important impact on the incomes of quota owners and growers and the location of production.

[64] James Joseph, The Tuna-Dolphin Controversy in the Eastern Pacific Ocean: Biological, Economic, and Political Impacts, 25 Ocean Dev. & Int'l L. 1 (1994).

tuna provided that they could buy or lease unused DMLs from other vessels.

The assignment of property rights may also help overcome an ongoing and potentially acrimonious dispute over the harvesting of large whales. The International Whaling Commission (IWC) agreed to a total moratorium of commercial whaling, beginning in 1986, in response to concerns about the sustainability of whale populations. Norway, Japan, and the former Soviet Union (now Russia) filed objections to the moratorium, thereby giving themselves the option to harvest whales while remaining IWC members, but Japan subsequently rescinded its formal objection. Some members of the IWC favor an indefinite ban on commercial harvesting, which, if implemented, may force countries such as Japan, Denmark, and Norway into a competing whaling organization.[65] An alternative, which helps address the concerns of those for and against harvesting, is to create tradeable property rights for whales that would be assigned to IWC members. In this way, individuals, environmental and animal rights groups, or even other IWC members who wish to prevent whale harvesting could purchase or lease whale harvesting units (WHUs) and thus reduce the allowable harvest.

More generally, a property rights approach to the ''tragedy of the commons'' is receiving increased attention by policy makers. One of the more successful pollution permit schemes has been the sulfur dioxide (SO_2) allowances allocated to U.S. coal-fired electric utilities, defined under Title IV of the U.S. 1990 Clean Air Act Amendments.[66] The act requires that each utility have an allowance for each ton of SO_2 emitted in a 12-month period. The property right is fully divisible (in tons of SO_2), is transferable, and can be banked and used in future years, while exclusivity of the right is achieved by financial and legal penalties and a requirement that there be continuous monitoring of emissions of each smokestack. The well-developed characteristics of the emission allowances have contributed to the success of the program. A declining annual cap for allowances has encouraged active trading, such that almost 12 million allowances were sold from the inception of the program up until to March 1997.[67] As with individual harvesting rights in the BC halibut fishery, tradable and private property rights

[65] John A. Knauss, The International Whaling Commission—Its Past and Possible Future, 28 Ocean Development & Int'l L. 79 (1997), observes that the basis for such an organization already exists with the North Atlantic Marine Mammal Committee (NAMMCO), which was formed in 1992 after Iceland left the IWC. Current members are Denmark (Greenland, Faroes), Iceland, and Norway.

[66] Paul L. Joskow & Richard Schmalensee, The Political Economy of Market-Based Environmental Policy: The U.S. Acid Rain Program, 41 J. Law & Econ. 37 (1998).

[67] Paul L. Joskow, Richard Schmalensee, & Elizabeth M. Bailey, The Market for Sulfur Dioxide Emissions, 88 Am. Econ. Rev. 669 (1998).

for SO_2 emissions may be described as a ‘‘a very valuable policy tool that has proven itself superior to traditional methods.’’[68]

VIII. Concluding Remarks

The ‘‘privatization’’ of the BC halibut fishery is a natural experiment of the effects of changes in property rights in a common-pool resource. The introduction of private harvesting rights in 1991 led to an important transformation in the industry and the behavior of fishers. In particular, the creation of an exclusive harvesting right allowed for an increase in the fishing season from just 6 days in 1990 to over 6 months in 1991 and over 8 months since 1992. A longer fishing season has allowed fishers to increase the quality of the fish landed and has enabled them to sell almost all of their harvest as a higher priced fresh product. As a result, unit quota rents and producer surplus per pound significantly increased between 1988 and 1991 and again between 1991 and 1994. Surveys of fishers also indicate that private harvesting rights made fishing safer, reduced losses of fishing gear, and decreased wastage of fish. Further, a shift in the property rights regime led to greater cooperation or co-management between the fishers and the regulator. Such improvements would not have been possible under the previous property rights structure where fishers tried to catch as many fish as possible in a very limited period of time.

The results suggest that ensuring an exclusive property right with a good quality of title is sufficient to yield substantial gains in revenues and producer surplus. For instance, between 1988 and 1991 observed producer surplus per pound increased by 52 and 89 percent, for small and large vessels, and between 1991 and 1994 rose by 25 percent for both vessel classes. Nevertheless, total producer surplus would have been even higher without restrictions on transferability in 1991 and 1992. Despite these gains, short-run cost efficiency did not increase between 1988 and 1991. However, substantive evidence exists for improvements in short-run cost efficiency from 1991 to 1994—a period that coincides with an improvement in the transferability, divisibility, and duration characteristics of the property right. Moreover, if fishers had been freely able to adjust their vessel size, which they were prevented from doing by vessel size restrictions set by the fisheries regulator, the average long-run technical cost efficiency of the halibut fleet would have been five times greater.

The study provides a number of insights to regulators of common-pool resources who wish to reap the potential benefits of ‘‘privatizing the com-

[68] Richard Schmalensee *et al.*, An Interim Evaluation of Sulfur Dioxide Emissions Trading, 12 J. Econ. Persp. 53, 67 (1998).

mons.'' First, gains in short-run cost efficiency from privatization may not be instantaneous and may be limited by restrictions on characteristics of the property right, especially transferability, divisibility, and duration. Second, substantial costs may exist in terms of long-run efficiency from the bundling of property rights with capital. Such costs suggest that regulators should consider the impact of preexisting regulations and institutional structures (for example, rate-of-return regulations for coal-fired electric utilities) when devising changes in property rights (such as the introduction of tradeable discharge sulfur dioxide permits). These considerations are especially important in industries where firms produce a range of outputs, each of which may be separately regulated. Third, the gains from privatization may not just be in terms of input usage and cost efficiency, but substantial benefits can also arise from the output side, in terms of revenue and product form.

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