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Firm behavior under quantity controls: The theory of virtual quantities ☆

Dale Squires *

NOAA Fisheries, 8901 La Jolla Shores Drive, La Jolla, California 92037, United States

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ABSTRACT

The theory of virtual quantities, the dual to virtual prices, provides a framework to analyze competitive multiproduct firm behavior under multiple quantity controls on inputs and outputs, including command-and-control quotas and transferable property rights. The framework addresses the firm's reactions to regulatory controls, impacts of adding or dropping quantity controls, inferring unrationed from rationed production, and conversion from command-and-control quotas to cap-and-trade systems with transferable property rights and secondary market behavior. The paper develops reasons for failure of quasi-concavity of technology, extends the elasticity of intensity's properties, and integrates the virtual price and virtual quantity frameworks. Virtual quantities are applied to assess potential firm responses to quantity controls and a potential transferable property right in a Malaysian fishery.

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Introduction

How should competitive multiproduct firm behavior be analyzed in a positive framework when there are multiple quantity controls on inputs and outputs? Bennear and Stavins (2007, page 113) emphasize that, “The use of multiple policy instruments is the norm, rather than the exception in environmental and natural resource management.” Nearly all policy analysis evaluates the relative merits of different – and single – policy instruments, and when analyzing the economic properties of combinations of multiple instruments, hybrid instruments receive particular attention, but these combinations of a quantity and a price instrument are rare (Bennear and Stavins, 2007).

Instead, regulation is often implemented through multiple quantity controls, notably command-and-control quotas, and these are increasingly converted to transferable property rights in cap-and-trade systems. Unique issues arise when regulating multiple inputs and outputs that the literature has yet to fully appreciate and which pose problems for the regulator. The competitive multiproduct firm's reaction to multiple quantity controls can be difficult to predict, because firm behavior – due to the interaction between the controls and unregulated inputs and outputs – can be unexpected. The firm's reaction is rooted in the production technology and the multiproduct structure of costs and revenues. The regulator would clearly benefit from understanding the competitive multiproduct firm's behavior under multiple quantity controls.

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* Fax: +1 858 546 7003.
E-mail address: dsquires@ucsd.edu

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The theory of quantity controls that analyzes competitive firm behavior under multiple quantity controls has largely focused upon an ex ante framework through virtual prices.[1] This theory of rationing and quotas has given less attention to a framework in which some of the inputs and outputs are already rationed, fixed, or primary, existing quotas are removed or added through deregulation or changes in regulations, or command-and-control programs are converted to cap-and-trade systems with transferable rights or credits.

The theory of virtual quantities provides the framework for positive analysis of existing quotas, rations, credits, property rights, fixed or primary factors and outputs, public goods and bads, or common resources – hereafter collectively referred to as quantity controls. Virtual quantities, dual to virtual prices, were originally called virtual endowments and analyzed effects of imposing fixed prices upon otherwise flexible prices in international trade (Neary, 1985). This framework has yet to be developed for a more general regulatory context or applied empirically.

This paper extends the theory of virtual quantities to analyze the competitive multiproduct firm's behavior under multiple in situ quantity controls for a normal technology (Sakai, 1974), in which input–output relationships are not regressive, and which is joint-in-inputs. The paper develops the firm's equilibrium inverse derived demand functions for existing quantity controls that underpin secondary markets for transferable property rights (credits) and cap-and-trade systems and develops their comparative statics to show secondary markets' and firms' responses to changes in quantity controls and market or accounting prices.[2] The paper clarifies several issues that arise when applying virtual quantities and virtual prices. First, it examines the relationship between rationed and unrationed production.[3] Second, it clarifies the relationship between shadow and virtual prices, unit quota rents, and implicit unit tariffs. Third, it examines failure of quasi-concavity, which potentially becomes more severe as additional quantity controls are added or regulated outputs or inputs are disaggregated, such as total greenhouse gasses into individual regulated gasses or total fish catch into individual species. Fourth, it rigorously decomposes quasi-rent into quantity control surplus and income. The paper develops additional properties under multiple quantity controls for the elasticity of intensity, which measures substitution or complementarity possibilities between an unregulated variable input or output and quantity control (Diewert, 1974). The paper integrates the dual virtual price and quantity frameworks for quantity controls. Finally, the paper integrates the virtual quantity framework with the closely related production framework of fixed factors (Sakai, 1974; Diewert, 1974; Lau, 1976), developing unique aspects that arise with quantity controls.

The virtual quantity framework is applied to an empirical study of input regulation in an industry exploiting a common resource, a Malaysian fishery. Multispecies tropical fisheries rely upon input rather than output controls to limit catches and fishing mortality due to the complex multitude of species and difficulties in resource stock assessments in data-poor environments, plus limited infrastructure for monitoring and enforcement. Program success depends, in part, on whether firms can substitute unrestricted inputs for the quantity-controlled inputs, which would then expand potential fishing capacity and fishing mortality beyond regulatory targets. The empirical results demonstrate no potential for firms to substitute unrestricted for restricted inputs. The pervasive input complementarity instead points to input controls that can lower harvest pressures on the common resource stock. The empirical section, through a simulation of a cap-and-trade, transferable property rights program for vessel length, demonstrates considerable potential for arbitrage efficiency and rent gains.

Virtual quantities establishes the virtual quantity framework and equilibrium inverse derived demand functions that underpin cap-and-trade markets, firm behavior, and local Le Chatelier effects for changes in price-quantity relationships when adding or dropping quantity controls. *Quasi-concavity of fixed inputs and outputs* develops conditions under which quasi-concavity fails with multiple quantity controls or fixed inputs or outputs. *Shadow prices and virtual prices* clarifies the difference between shadow and virtual prices and relates the unit rent, inverse derived demand, shadow price, and virtual price functions under the rationing, production, and welfare theory frameworks. *The elasticity of intensity* extends the elasticity of intensity to multiple quantity controls. *Empirical application* empirically illustrates virtual quantities by analyzing public regulation of fishing firms using input controls in Malaysia. *Concluding remarks* concludes. Five online appendices provide supplementary information. Appendix A gives proofs of propositions, Appendix B gives details and derivations for empirical profit function formulae, Appendix C discusses data, Appendix D derives fundamental equations, and Appendix E discusses calculation of, and provides formulae for, quota quasi-rent in a transferable effort program with a cap-and-trade secondary market.

[1] Virtual prices are those prices that would induce an unconstrained firm to demand the level of the rationed variable input or output or quota. Neary and Roberts (1980) give a formal definition and proof of existence. Virtual prices with production are formally defined later in the paper. Rothbarth (1941) first proposed the virtual price approach to (consumer) rationing, which Neary and Roberts (1980) extended to consumer duality theory. Neary (1985), Squires and Kirkley (1991), Anderson and Neary (1992), Fulginiti and Perrin (1993), Segerson and Squires (1993), Squires (1994), and Roberts (1999) extended the virtual price approach to producer rationing and quotas; Thomsen (2000) to fixed factors; Squires and Kirkley (1995, 1996) and Vestergaard (1999) to transferable quotas, property rights, and inverse derived demand systems; and Mäler (1974), Hanemann (1991), and Carson et al. (1998) to consumption and valuation of public goods.

[2] Accounting price is used rather than shadow price to distinguish situations other than those arising with quantity controls and fixed netputs. Accounting prices capture all sources of economic value and account for missing, incomplete, and distorted markets. The accounting price of a netput is defined as the marginal effect on social welfare of the availability of an extra unit of the specified netput (Dréze and Stern, 1996). Shadow price in this paper refers to quantity controls.

[3] Quantity controls exceeding their virtual quantities correspond to forced or subsidized production, but are not explicitly considered here.

Virtual quantities

This section: provides intuition into virtual quantities and virtual prices; generalizes Neary's (1985) virtual quantity framework; reinterprets shadow price functions as equilibrium inverse derived demand functions that underpin command-and-control quantity controls and transferable property rights and develops their comparative statics; and analyzes local Le Chatelier effects.

Intuition

A virtual quantity is the quantity of an input or output that the initially quantity-constrained firm would demand or supply once unconstrained, given that quantity control's market or accounting price. Derived demands of initially fixed quantity controls are inverse with endogenous implicit marginal valuations. An exogenous market or accounting price is imposed, giving rise to the corresponding virtual quantity.

A virtual price is the price that would induce an initially unconstrained firm to demand or supply the level of input or output when under quantity control (Neary and Roberts, 1980). Virtual prices pertain to demand or supply that is direct and to inputs or outputs that are initially endogenous; quantity controls are then imposed, leading to corresponding virtual prices, unit rents, and notional supply and demand. Virtual prices do not generally correspond to market or accounting prices except when quantity controls or unpriced public goods or common resources are already at optimum levels.

In sum, the virtual price approach describes what currently unrationed production would look like if command-and-control or transferable quantity controls were imposed and the virtual quantity approach best asks what a rationed process would look like if existing quantity controls were lifted or adjusted or new ones added or when evaluating the transition from command-and-control to transferable quantity controls. The two approaches can also be combined.

Basics

Consider a firm with joint-in-inputs production, a normal technology and variable netput vector Y ($Y>0$ for outputs and $Y<0$ for inputs), and the competitive price vector $P>0$, taken as given. Defining netputs over geographic areas extends the analysis to areas of production, such as fishing grounds, although not pursued further here. The vector of fixed or rationed netputs can be divided into those adjusted over longer periods of time, K and those adjusted more frequently, L, with market rental or services prices $W>0$ and $Q>0$ (or accounting prices for unpriced inputs or outputs that are public goods or bads or common resources), respectively, where $K,L>(<)0$ for outputs (inputs). K might be plant and L might be equipment and pollution controls such as coal scrubbers, or K might be natural resource endowments and L might be fixed factors in models of international trade, K and L might be rationed outputs, or K might be land and L family or other forms of labor. The firm's production technology is described by its restricted (variable) profit function, $\pi[P,L,K]=\max_Y\{PY:(Y,L,K)\epsilon T\}$, where T is the technology set and PY is the dot or inner product (Sakai, 1974).[4] When unconstrained by quantity controls L, the restricted profit function is: $\pi[P,Q,K]=\max_{Y,L^*}\{PY+QL^*:(Y,L^*,K)\epsilon T\}$, where L^* denotes freely variable netput (s) corresponding to L, by Hotelling's Lemma, $\pi_Q[P,Q,K]=L^*$, and $\pi[P,Q,K]$ shares properties with $\pi[P,L,K]$ (with one less fixed netput).

Shadow prices of K and L, which give the firm's implicit marginal valuations of K and L, are defined as (Diewert, 1974; Sakai, 1974; Lau, 1976): $\pi_K[P,L,K]=\omega$ and $\pi_L[P,L,K]=\psi$. They measure the effect on $\pi[P,L,K]$ of a marginal increase in one of the quantity controls K or L. These shadow price (factor reward) functions are equilibrium inverse derived demand functions for K and L that take account of the total optimal adjustment of all variable inputs and outputs given P,L,K, and technology (Vestergaard, 1999). The shadow price functions are linearly homogeneous in P, non-decreasing in P when $Y>0$, non-increasing in P when $Y<0$, and non-decreasing in K and L (from quasi-concavity of $\pi[P,L,K]$ in K and L, discussed next).

Quasi-concavity of $\pi[P,L,K]$ in K and L is a natural extension of a quasi-concave production function for scalar output, and follows from the assumed quasi-convexity of the technology (Diewert, 1974; Lau, 1976).[5] Quasi-concavity of $\pi[P,L,K]$ in K and L requires the matrix $\pi_{KL}[P,L,K]\le 0$, where by Young's Theorem $\pi_{LK}[P,L,K]=\pi_{KL}[P,L,K]$.[6] Negative semi-definiteness implies that the inverse derived demand functions are non-increasing in their own quantities, i.e. $\pi_{LL}[P,L,K]\le 0$ and $\pi_{KK}[P,L,K]\le 0$, are not upward sloping, and implicit marginal valuations or shadow prices are non-negative, i.e. $\pi_K[P,L,K]\ge 0$, $\pi_L[P,L,K]\ge 0$.[7] Quasi-concavity also implies that as L or K become arbitrarily large, $\pi_{LL}[P,L,K]$ or $\pi_{KK}[P,L,K]$

[4] π is continuous, linearly homogeneous, and convex in P; π is nondecreasing in P for $Y>0$ and nonincreasing in P for $Y<0$ for every set of fixed factors and outputs; and π is continuous, nondecreasing, and quasi-concave in fixed factors and outputs, i.e. in fixed netputs (Diewert, 1974; Sakai, 1974). Further assume that π is twice differentiable in all its arguments. In trade models, π is assumed linear homogeneous in fixed factors to insure competitiveness.

[5] Lau (1976), Eqs. (3)–(11), develops the relationships between quasi-concavity of π and quasi-convexity of the production function F and between the Hessians of F and π. Negative semi-definiteness of F's Hessian corresponds to quasi-concavity of π in fixed factors or outputs.

[6] π_i denotes the vector of first partial derivatives of π with respect to quantity control i and denotes the matrix of second partial derivatives with respect to quantity controls i and j.

[7] This corresponds to the law of inverse demand for inverse demand systems in consumer theory. The matrix π_{KL} corresponds to the Antonelli matrix of inverse consumer demand or inverse derived demand or unit rent functions for transferable quotas. If the reciprocity conditions hold, i.e. symmetry by Young's Theorem, then $\pi_{KL}=\pi_{LK}$. Factor price equalization would yield $\pi_{KK},\pi_{LL}=0$ (Neary, 1985).

approach zero and correspond to non-increasing marginal rates of substitution or transformation between pairs of these inputs or outputs (Lau, 1976).

The full static equilibrium levels of both K and L are found by simultaneously solving the first-order conditions: $\pi_K[P,L,K]=W$ and $\pi_L[P,L,K]=Q$ (Diewert, 1974). To be consistent with long-run profit maximization, second-order conditions for K and L are those of quasi-concavity.

The virtual quantity of L, $L^*(P,Q,K)$, is defined implicitly by (Neary, 1985) as:

$$\pi_L\left[P,L^*,K\right]=Q. \tag{1}$$

The virtual quantity vector, $L^*(P,Q,K)$, is derived by solving for the partial static equilibrium level of L, while allowing K to remain fixed, given P, Q, and technology. Since fixed netputs are simply quantity controls that vanish in the long run, the virtual quantity vector for the fixed netput vector L corresponds to the partial static equilibrium values given K and L and corresponds to variable netputs when evaluated at L^*.

The shadow price function for K, when evaluated at $L^*(P,Q,K)$ rather than observed L, is:

$$\widehat{\pi}_K\left[P,L^*(P,Q,K),K\right]=\widehat{\omega}. \tag{2}$$

The "hat" symbol (^) denotes a restricted profit or shadow price function evaluated at the virtual quantity vector $L^*(P,Q,K)$ rather than the given quantity control L with K still held fixed, i.e. the hat denotes a function unconstrained by fixed L and evaluated at $L^*(P,Q,K)$.

The restricted profit functions unconstrained and constrained by L are related:

$$\pi[P,Q,K]=\widehat{\pi}\left[P,L^*(P,Q,K),K\right]-QL^*(P,Q,K), \tag{3}$$

when evaluated at $L^*(P,Q,K)$. $\pi[P,Q,K]$ gives restricted profits when L is a variable input at its restricted-profit maximizing level with K remaining fixed, $L^*(P,Q,K)$. $\widehat{\pi}\left[P,L^*(P,Q,K),K\right]$ gives restricted profits with L fixed at the level $L^*(P,Q,K)$, but does not account for the costs of production associated with $L^*(P,Q,K)$. $QL^*(P,Q,K)$ accounts for these associated costs of production associated with $L^*(P,Q,K)$.

The shadow price of K that is unconstrained and constrained by L evaluated at $L^*(P,Q,K)$ is found by differentiating (3) by K to give:

$$\pi_K[P,Q,K]=\widehat{\pi}_K\left[P,L^*(P,Q,K),K\right], \tag{4}$$

or $\omega=\widehat{\omega}$, since at $L^*(P,Q,K)$ the first-order condition is $\widehat{\pi}_L\left[P,L^*(P,Q,K),K\right]-Q=0$. In addition, making use of (3) gives $\widehat{\pi}_Q=L^*(P,Q,K)=\pi_Q[P,Q,K]$, which is Hotelling's Lemma. Also, $\widehat{\pi}_L\left[P,L^*(P,Q,K),K\right]=Q$ at the optimum.

The optimal vector of variable netputs supplied/demanded under quantity controls evaluated at $L^*(P,Q,K)$ is identical to the optimal unconstrained vector:

$$\widehat{Y}=\widehat{\pi}_P\left[P,L^*(P,Q,K),K\right]=\pi_P[P,Q,K]. \tag{5}$$

Inverse derived demand functions

The firm's equilibrium inverse derived demand functions for quantity controls, $\pi_L[P,L,K]$ and $\pi_K[P,L,K]$, are central to analyzing existing command-and-control programs and transferable property rights (credits), including individual transferable quotas (ITQs) and individual transferable effort (ITE), and their cap-and-trade secondary markets when conversion from command-and-control to cap-and-trade is planned.[8] These functions allow measuring unit rents, producer welfare, and gains from trade (arbitrage efficiency) with transferable rights, and assessing impacts upon unit rents and firm responses to quantity control changes, the number of quantity controls to impose, and other firm and secondary market behavior.

Their horizontal summation gives market inverse derived demand for ITQs or ITEs for rivalrous outputs or inputs, and equating each market demand with its corresponding aggregate industry quantity control gives ITQ or ITE prices in secondary markets that equal optimum unit rents. Thus the market ITQ/ITE price is solved for say a single quota L by equating aggregate quota $\overline{L}$ with $\sum_m\pi_L[P,L,K]$ or simultaneously solving both $\sum_m\pi_L[P,L,K]$ and $\sum_m\pi_K[P,L,K]$ with both $\overline{L}$ and $\overline{K}$,m = 1, …,M, for M firms. Since $\sum_m\pi_L[P,L,K]$ and $\sum_m\pi_K[P,L,K]$ are equilibrium functions, economic welfare is measured by integrating these curves, which is necessary for only one of them if the curve pertains to a necessary netput when there are multiple quotas (Vestergaard, 1999).[9] Should L become variable and evaluated at $L^*(P,Q,K)$ and an ITQ/ITE placed upon K, equating aggregate quota $\overline{K}$ with $\sum_m\widehat{\pi}_K\left[P,L^*(P,Q,K),K\right]=\widehat{\omega}$ rearranged in terms of K and evaluated at $\overline{K}$ allows solving for the equilibrium market ITQ/ITE price ω^*, where * denotes optimum. Welfare changes from arbitrage efficiency due to quota

[8] Squires and Kirkley (1996), Vestergaard (1999) apply the virtual price approach to develop equilibrium inverse derived demand functions to evaluate a multiproduct fishery and potential cap-and-trade secondary markets when the industry is currently unregulated by individual quotas and has yet to receive ITQs.

[9] A necessary netput is one for which a $Y>(<)\,0$ is required for the firm to continue to operate (Just et al., 2005). In fisheries, if ex-vessel fish landings data are used, economic welfare of producers, processors, distributors, wholesalers, retailers, and consumers is measured.

trade are found by differencing the changes in corresponding areas before and after quota trade. The empirical section illustrates and provides full details.

The following Propositions summarize producer welfare measurement:[10]

Proposition 1. (Vestergaard, 1999) For a multiproduct firm under joint-in-inputs technology, producer welfare with multiple quantity controls can be equivalently measured either in the netput market or as the area under the equilibrium inverse derived demand curve of the quantity control for a necessary netput, which is in the secondary market if a transferable property right.

Proposition 2. (Rucker et al., 1995). The quasi-rent is comprised of a quantity control income, which is the shadow price multiplied by the quantity control quantity or the quantity control price multiplied by the transferable property right in a secondary market of a cap-and-trade system, and quantity control surplus, which is the remaining area under the inverse derived demand curve.

Analyzing the interaction between quantity controls requires evaluating the impact of changes in one quantity control on the inverse derived demand function of the other control as well as the impact of the own change in quantity control on its own inverse derived demand function. This is given by the Antonelli matrix of inverse derived demand functions, $[\pi_{LK}[P,L,K]]$, which gives the regulator insight into firm and secondary market behavior under programs of both command-and-control and transferable quantity controls. After exogenous shocks, firms readjust production to equate marginal unit rents across all quantity controls. Evaluating these unit rents and their responses to changes in exogenous market or accounting prices or quantity controls allows the regulator to anticipate potential firm and secondary market responses to changes in markets and regulations and spillover effects. Hicks (1956) notion of quantity into price is appropriate when L, $K>0$ or L, $K<0$: $\pi_{KL}[P,L,K]=\pi_{LK}[P,L,K]>(<)0$ for q-complements (q-substitutes). For two fixed factors, $\pi_{KL},\pi_{LK}>0$. For a normal technology and say $L>0$ and $K<0$, $\pi_{LK}[P,L,K]>0$ corresponds to a scale flexibility that shifts out inverse derived demand. $\pi_{LL}[P,L,K]\le 0$ and $\pi_{KK}[P,L,K]\le 0$ and for own effects is a counterpart to the law of inverse demand in consumer theory.

Changes in exogenous market or accounting prices of unregulated netputs shift the firm's and secondary market's inverse derived demand functions in ways the regulator can anticipate. Small changes in net unit rent flexibilities corresponding to Antonelli matrix terms indicate relative stability in the face of exogenous shocks. Price stability lowers uncertainty and provides more stable planning and regulatory environments. When $Y>0$ and $K>0$ are substitutes (complements), command-and-control unit rents and equilibrium ITQ prices (equal to optimal unit rents) should rise (fall) when $\pi_{KP}[P,L,K]<(>)0$. Under command-and-control and transferable input controls with ITE secondary markets, $Y<0$, and $K<0$, comparable effects exist.

Next consider comparative statics of inverse derived demand functions with existing K when converting command-and-control L to an ITQ or ITE program – the typical transition rather than from unregulated production (which would be evaluated by virtual prices).[11] These comparative statics underpin gross unit rent flexibilities. Differentiating (4) by K and evaluating at $L^*(P,Q,K)$ give $\pi_{KK}=\widehat{\pi}_{KK}+\widehat{\pi}_{KL}L_K^*$. From the Antonelli matrix, signs of π_{KK}, $\pi_{KL}=\widehat{\pi}_{KL}+\widehat{\pi}_{KL}L_L^*$, and $\pi_{KP}=\widehat{\pi}_{KP}+\widehat{\pi}_{KL}L_P^*$ are as above, but evaluated at $L^*(P,Q,K)$ rather than L. Comparative statics can be decomposed into pure substitution effects, $\widehat{\pi}_{KL}$, expansion effects, $\widehat{\pi}_{KL}L_L^*$, and corresponding net and gross elasticities for unrationed and rationed production (Sakai 1974; Squires, 1994). Comparable comparative statics are found for the inverse derived demand function for L, with unit rents equal to ITQ/ITE prices at the optimum, through differentiating $\widehat{\pi}_L\left[P,L^*(P,Q,K),K\right]$ by L, K, or P and evaluating at $L^*(P,Q,K)$.[12] Derivatives of (5) give impacts of changes in quantity controls or exogenous market or accounting prices on unregulated variable netput supply/demand. The following Proposition summarizes the comparative statics with and without variable L evaluated at $L^*(P,Q,K)$:

Proposition 3. Changes in exogenous quantity controls and market and accounting prices for unregulated netputs shift inverse equilibrium derived demand functions of quantity controls, alter unit rents and total profits, and change equilibrium secondary market prices for transferable quantity controls with transferable property rights.

With L, $K>0$ and ITQs, the industry product transformation frontier for quotas limits adjustments in ITQ portfolios and ITQ price (optimum unit rent) stability with quota trade. The marginal rate of product transformation between L and K, MRPT_{KL}, describes the frontier's slope and curvature and at the ITQ secondary market equilibrium equals the ratio of the optimum unit rents: $\text{MRPT}_{KL}=-dL/dK=\omega^*/\psi^*$ Once exogenous overall quotas $\overline{K}$ and $\overline{L}$ are set, endogenous MRPT_{KL} at that point on the frontier determines the market clearing price ratio ω^*/ψ^*. Changes in exogenous $\overline{K}$ and $\overline{L}$, and hence endogenous $\text{MRPT}_{KL}=\omega^*/\psi^*$, establish the potentially nonhomothetic output quota expansion path. A comparable situation exits

[10] Even if the netput is not necessary, it is possible to measure changes in quasi-rent due to a price change of the netput in the associated netput market (Vestergaard, 1999). See Vestergaard (1999) for the mechanics of welfare measurement and also Fulginiti and Perrin (1993) for producer welfare measurement in the netput market. See Rucker et al. (1995), Squires and Kirkley (1996), Vestergaard (1999) for welfare measurement under an inverse derived demand curve for a single quota. For Proposition 2, see Fig. 2 and Eqs. (11) and (17) of Vestergaard (1999).

[11] See Squires and Kirkley (1996), Vestergaard (1999) for the virtual price approach.

[12] Differentiating $\pi[P,Q,K]=\widehat{\pi}\left[P,L^*(P,Q,K),K\right]-QL^*(P,Q,K)$ by L gives $\pi_L[P,Q,K]=\ \widehat{\pi}_L\left[P,L^*(P,Q,K),K\right]-Q$, and further differentiation gives $\pi_{LL}[P,Q,K]=\ \widehat{\pi}_{LL}\left[P,L^*(P,Q,K),K\right]$, etc.

for $L, K < 0$ and ITEs with the industry isoquant, marginal rate of input substitution, endogenous ITE prices that adjust to clear ITE markets, and input quantity control expansion path. Proposition 4 summarizes.

Proposition 4. For quantity controls, the virtual quantity framework provides the product transformation frontier or input isoquant, the marginal rate of product transformation or substitution, secondary market equilibrium prices and price ratios, and quantity control expansion path.

Local Le Chatelier effects

Dropping or adding quantity controls affect responsiveness of the firm's and secondary market's own endogenous ITQ/ITE price, including inverse derived demand functions and unit rents, to changes in exogenous market or accounting prices and quantity controls, indicated by local Le Chatelier effects (Samuelson, 1947). Roberts (1999, p. 416) defines the local Le Chatelier principle as, "… if variables in a system are chosen to optimize a function then, as a result of small structural changes to the system, e.g. a small change in prices, the responsiveness of the chosen variables will be reduced when extra constraints are added to the optimization problem." When evaluating property rights programs, regulators can anticipate these responses to adding, dropping, tightening, or relaxing quantity controls, which in turn inform decisions about the number of quantity controls to impose, stability of unit rents, secondary market ITQ/ITE prices, and firms' allocations of production across quantity controls.

The local Le Chatelier effect of removing or adding a quantity control L for the response in shadow prices (unit rents) of K to changes in K evaluated at the virtual quantity vector $L^*(P,Q,K)$ is given by the difference between two positive semi-definite matrices:

$$\widehat{\pi}_{KK} - \pi_{KK} = -\widehat{\pi}_{KL}\left[\widehat{\pi}_{LL}\right]^{-1}\widehat{\pi}_{KL} \geq 0, \tag{6}$$

where $\widehat{\pi}_{KK}, \widehat{\pi}_{KL}$, and $[\widehat{\pi}_{LL}]^{-1}$ are derivatives of $\pi[P,L,K]$ evaluated at $L^*(P,Q,K)$, i.e. derivatives of $\widehat{\pi}\left[P, L^*(P,Q,K), K\right]$. Proposition 5 summarizes this well-known result, but within the context of inverse derived demand functions with quantity controls.

Proposition 5. As quantity controls are removed (added), responsiveness of the firm's remaining quantity controls' shadow prices (unit rents) and corresponding cap-and-trade market's price-quantity responsiveness to changes in their own quantities increases (decreases), independently of q-substitution or q-complementarity. The more inelastic the inverse derived demand for the quantity controls removed or added, the stronger is the change in responsiveness for the remaining quantity controls' shadow prices or transferable quantity control market prices. Ratios of market clearing endogenous optimum unit rents in secondary markets, equaling marginal rates of transformation or substitution between transferable property rights, are also altered.

The local Le Chatelier effect from removing or adding quantity controls L on net price responsiveness of variable (unregulated) output supply and input demand to changes in market and accounting prices, i.e. the difference in responses constrained and unconstrained by L, using (5) evaluated at $L^*(P,Q,K)$, is given by Proposition 6 and written as (Lau, 1976, Neary, 1985):

$$\widehat{Y}_P - Y_P = -\widehat{\pi}_{PL}\left[\widehat{\pi}_{LL}\right]^{-1}\widehat{\pi}_{LP} \geq 0. \tag{7}$$

Proposition 6. Removing (imposing) an additional quantity control L increases (decreases) the firm's net variable output supply or input demand responsiveness to changes in own prices.

Thus for $Y > 0$, $\widehat{Y}_P \geq Y_P \geq 0$ and for $K < 0$, $0 \geq \widehat{\pi}_{KK} \geq \pi_{KK}$. Moreover, the inequalities become equalities if and only if the netputs are additively separable (Lau, 1976).

Proposition 7. Total multiproduct rents under transferable property rights are smaller than the sum of the individual rents of single-product ITQs for comparably sized aggregate quotas due to local Le Chatelier effects. The additional constraints limit feasible regions and reorganizations in production to changes in exogenous market and accounting prices and quotas. A comparable result holds for ITEs.

Quasi-concavity of fixed inputs and outputs

Potential failure of quasi-concavity grows when progressively applying multiple quantity controls in a multiple-product and multiple-input framework because of the growing possibility of quasi-concavity failure.[13] This failure can potentially become an issue as additional quantity controls are added or dropped or aggregate outputs or inputs under quantity controls are disaggregated, such as total fish catch disaggregated by species. This section examines conditions under which

[13] Quasi-convexity relates to constrained maximization problems, whereas convexity relates to unconstrained maximization. Strict quasi-convexity and quasi-concavity is denoted by $>$ and quasi-concavity is denoted by $\geq$.

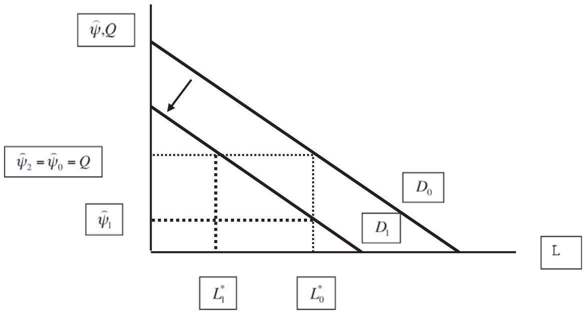

Fig. 1. Failure of concavity when a quantity control on netput l is removed.

quasi-concavity can fail under multiple quantity controls and potential implications for firm behavior when designing regulations.

Perverse incentives for firms can arise under quasi-concavity failure, such as overinvestment in the capital stock and subsequent sub-optimal levels of the capital stock, fueling increasing overcapacity in fisheries and pressures on fishing mortality rather than expected decreases. Secondary markets in cap-and-trade systems can fail to reach equilibrium or have unstable equilibriums if reached, where a price above market equilibrium with upward sloping inverse derived demand leads to excess quantity demanded and further price increases.

More formally, quasi-concavity of $\pi[P,L,K]$ in K can fail, leading to $\hat{\pi}_{KK}\left[P,L^*(P,Q,K),L\right] > 0$. The inverse demand (shadow price/unit rent) function for K can slope upward when L is constrained or the constraint is eased, even though the shadow prices are nonnegative and the Le Chatelier effect holds. Perverse investment signals for K result. Thus, $\pi_K[P,L,K] \geq 0$ and $\hat{\pi}_{KK}\left[P,L^*(P,Q,K),K\right] > \pi_{KK}[P,Q,K]$ from (6), but $\hat{\pi}_{KK}\left[P,L^*(P,Q,K),K\right] > 0$, even though $\pi_{KK}[P,Q,K] \leq 0$.

Eq. (8) below is used to evaluate the impact of adding additional quantity controls upon quasi-concavity. Eq. (8) defines the relationship between the responsiveness of the inverse demand functions for K unconstrained by L, $\pi_{KK}[P,Q,K]$, and constrained by L and evaluated at $L^*(P,Q,K)$, $\hat{\pi}_{KK}\left[P,L^*(P,Q,K),K\right]$. Rearranging (6) gives $\hat{\pi}_{KK} = \pi_{KK} - \hat{\pi}_{KL}L_K^*$, or:

$$\hat{\pi}_{KK} = \pi_{KK} - \hat{\pi}_{KL}\left[\hat{\pi}_{LL}\right]^{-1}\hat{\pi}_{KL}. \tag{8}$$

Now consider the conditions for failure of quasi-concavity that arise with multiple quantity controls. It is generally expected that $\hat{\pi}_{KK}\left[P,L^*(P,Q,K),K\right], \pi_{KK}[P,Q.K] \leq 0$, $-\hat{\pi}_{KL}[\hat{\pi}_{LL}]^{-1}\hat{\pi}_{KL} \geq 0$, and $\pi_{KK} - \hat{\pi}_{KL}[\hat{\pi}_{LL}]^{-1}\hat{\pi}_{KL} \leq 0$. However:[14]

Proposition 8. When adding or dropping quantity controls L, quasi-concavity of the profit function with respect to quantity controls remaining fixed, K, fails under four conditions or their combination: (1) L and K are strong q-complements or substitutes; (2) L and K are "just the right" combinations of several “weak” q-complements or substitutes of L and K; (3) the matrix of second-order derivatives of the restricted profit function with respect to the quantity controls added or dropped L and evaluated at their virtual quantities, $\hat{\pi}_{LL}$, is sufficiently large; and (4), when the shadow prices of the quantity controls evaluated at virtual quantities, $\hat{\pi}_{LL}$, themselves fail quasi-concavity.

Shadow prices and virtual prices

This section, by showing that shadow and virtual prices differ when quantity controls bite and by showing that shadow prices are equivalent to unit rents and implicit unit tariffs, explicates the conditions under which they should be used, and helps clarify the relationship between the production, trade, producer welfare, and rationing frameworks. Analyzing solely with virtual prices rather than unit rent functions or shadow prices, as is sometimes found in the literature, gives incorrect results as demonstrated here. The section also rigorously decomposes quasi-rent into quantity control income and surplus.

Virtual prices and associated profit functions are defined following Neary and Roberts (1980), Fulginiti and Perrin (1993), and Squires (1994). The restricted profit function initially restricted only by K remains $\pi[P,Q,K]$, the ex ante specification before a quantity control L, and when initially restricted by both K and L remains $\pi[P,L,K]$, the ex post specification. Virtual prices ϕ are defined as an implicit function of P, L, and K by the restriction that they are those prices that would induce a firm unconstrained by the quantity control L to demand/supply exactly L: $L = \pi_Q[P,\phi,K]$, where $\pi[P,\phi,K] = \max_Y(PY + \phi L : (Y,L,K)\epsilon T)$.[15] When $\pi[P,Q,K]$ is now constrained by quantity control L, so that $l = L < L^*(P,Q,K)$, the constrained restricted profit function is $\pi[P,Q,L,K] = \max_Y[PY + QL : (Y,L,K)\epsilon T]$. The constrained restricted profit function can be related to the restricted profit function unconstrained by L: $\tilde{\pi}[P,Q,L,K] = \pi[P,\phi,K] + [Q-\phi]L$, where $[Q-\phi]L$ is the profit compensation required to induce a firm unconstrained by L facing ϕ to produce the same as under L. Differentiating $\tilde{\pi}[P,Q,L,K]$ by L gives the shadow price or unit rent function: $\tilde{\pi}_L[P,Q,L,K] = \phi_L\left[\pi_\phi - L\right] + [Q-\phi] = [Q-\phi]$, i.e.

[14] Fig. 1 illustrates this result.

[15] Variable output supply ($Y > 0$) and variable input demand functions ($Y < 0$) will be a function of P, K, and ϕ rather than Q.

$\tilde{\pi}_L[P,Q,L,K]=\tau[P,Q,L,K]=[Q-\phi]$, where $\tau[P,Q,L,K]$ is the implicit unit tariff or unit quota rent (Anderson, 1988), $\tau[P,Q,L,K]>(<)0$ for outputs (inputs), and $\pi_Q-L=0$ by Hotelling's Lemma. At $Q=\phi, L^*=L$, and $\tau=0$, and at ϕ and $l=L<L^*$:

$$\tilde{\pi}_L[P,Q,L,K]=[Q-\phi]=\pi_L[P,L,K], \tag{9}$$

and

$$\tau[P,Q,L,K]=\psi[P,L,K]. \tag{10}$$

The following two Propositions summarize the relationships for $L<L^*$.

Proposition 9. The shadow price for a quantity control L derived within the virtual price framework, $\tilde{\pi}_L[P,Q,L,K]$ evaluated at virtual prices, ϕ, and the shadow price derived within the restricted profit function framework, $\pi_L[P,L,K]$, are equivalent.

Proposition 10. Equivalently, the unit rent or implicit unit tariff for L from the virtual price framework, evaluated at virtual prices, equals the shadow price from the "standard" production framework.

The next two propositions clarify virtual prices vis-à-vis shadow prices and allow easily calculating virtual prices from shadow prices (e.g. derived from linear programming, Lagrange multipliers from marginal changes in social welfare functions with respect to netputs, etc.).

Proposition 11. Shadow prices do not equal virtual prices when quantity controls that are added or dropped do not equal their virtual quantities, i.e. when $L\neq L^*$.

Proposition 12. Virtual prices equal corresponding market or accounting prices minus shadow prices: $Q-\tilde{\pi}_L[P,Q,L,K]=Q-\pi_L[P,L,K]=\phi$.

The next Proposition rigorously defines Proposition 2 within the virtual price framework by decomposing quasi-rent under quantity controls into quota income and surplus.[16]

Proposition 13. *$\pi[P,\phi,Z]$ corresponds to the quota surplus and $[Q-\phi]L$ corresponds to the quota income.*

The elasticity of intensity

This section assesses how the net and gross substitution possibilities between unregulated netputs and quantity controls change as quantity controls are added or dropped, and thereby the firm's reactions to such regulatory changes. When fishery managers restrict vessels' inputs to reduce overall effort and hence catches, vessels might substitute unregulated for regulated inputs to maintain catches if the production technology allows (Squires, 1987, 1994; Dupont, 1991). Regulators frequently then respond by regulating additional inputs to further bind up production, but regulators are unsure of the firm's response. Similarly, fishery managers set command-and-control quotas or transferable property rights species-by-species, but spillover effects from regulated to unregulated species can lead to increased fishing pressures upon the latter (Squires and Kirkley, 1991; Asche et al., 2007). Regulators can respond by placing additional species under quotas in a cat-and-mouse game, but firm reactions are again unknown and unanticipated. In contrast, overall fishing pressures can decline with complementarity between regulated and unregulated species.

The elasticity of intensity allows regulators to gauge potential firm reactions and spillover effects by measuring the net substitution possibilities between a variable netput and quantity controls (Diewert, 1974).[17] The properties of this elasticity have yet to be developed when quantity controls are added or dropped, which is the purpose of this section.

Net elasticity of intensity

The net elasticity of intensity between variable netput Y and quantity control K, given quantity control L, is derived from (5), $\gamma_{YK}=\frac{\partial lnY}{\partial lnK}=Y_K\left[\frac{K}{Y}\right]$, or (Diewert, 1974):

$$\gamma_{YK}=\pi_{PK}[P,L,K]\frac{K}{\pi_P[P,L,K]}. \tag{11}$$

The sign of γ_{YK} depends upon whether Y and K are inputs or outputs. When Y and K are both outputs (inputs), $\gamma_{YK}>(<)0$ when Y and K are p-complements (substitutes) (Diewert, 1974).[18] The implications of the sign for regulation are given by (Dupont, 1991; Asche et al., 2007):

[16] Here quota rather than the more general term quantity control is used to stay consistent with the use in the literature. Nonetheless, it should be understood that quota stands for the more general quantity control.

[17] Net elasticities refer to K and L that are both fixed and gross elasticities to K fixed and L variable and evaluated at its virtual quantity. Dupont (1991) develops the relationship between the elasticity of intensity and the conventional price elasticity of input demand.

[18] When one is input and the other output, expansion effects and output elasticities are relevant.

Proposition 14. Net complementarity (substitutability) between regulated and unregulated outputs decreases (increases) unregulated outputs with decreases (increases) in a quota-regulated output. The same spillover result holds between regulated and unregulated inputs.

Virtual quantities and the gross elasticity of intensity

The gross elasticity of intensity between unregulated variable netput Y and quantity control K when removing or adjusting quantity control L and evaluated at $L^*(P,Q,K)$ is:

$$\widehat{\gamma}_{YK}=\widehat{\pi}_{PK}\frac{K}{\widehat{\pi}_P}=\left[\pi_{PK}-\widehat{\pi}_{PL}[\widehat{\pi}_{LL}]^{-1}\widehat{\pi}_{LK}\right]\frac{K}{\widehat{\pi}_P}, \tag{12}$$

where $\widehat{\pi}_P=\widehat{Y}[P,L,K]$ and $\widehat{\pi}_{PK}=\widehat{Y}_K[P,L,K]$ (and $\widehat{\pi}_{KL}=\widehat{\pi}_{LK}$).[19] $-\widehat{\pi}_{PL}[\widehat{\pi}_{LL}]^{-1}\widehat{\pi}_{LK}$, an expansion effect, gives the change in responsiveness in π_{PK} and γ_{YK} from (11) due to the addition or removal of quantity controls L and can even reverse the sign of $\widehat{\pi}_{PK}$ and $\widehat{\gamma}_{YK}$ in (12) compared to π_{PK} and γ_{YK} in (11). When $\left|\pi_{PK}\right|>(<)\left|-\widehat{\pi}_{PL}[\widehat{\pi}_{LL}]^{-1}\widehat{\pi}_{LK}\right|$, the sign of $\widehat{\pi}_{PK}$ and $\widehat{\gamma}_{YK}$ is the same (opposite) as π_{PK} and γ_{YK} in (11). In short, tighter or looser regulatory regimes give different potentials to respond to regulations, not just directly through the net effects γ_{YK} or π_{PK}, but indirectly through the expansion effect $-\widehat{\pi}_{PL}[\widehat{\pi}_{LL}]^{-1}\widehat{\pi}_{LK}$. Proposition 15 summarizes.

Proposition 15. Adding or removing quantity controls alters the firm's gross substitution possibilities between unrestricted netputs and quantity controls in the firm's potential response to regulations. Substitution possibilities between quantity controls and unrestricted netputs can change from substitution to complementarity or the reverse if the quantity control expansion effects dominate the net substitution effects.

Elasticity of intensity and the Le Chatelier effect

Does the responsiveness of gross $\widehat{\gamma}_{YK}$ in (12) tighten up, loosen, or even reverse sign compared to net γ_{YK} in (11) when removing or adding a quantity control L? The answer, which lies in the local Le Chatelier effect for $\widehat{\gamma}_{YK}$, helps regulators anticipate changes in responsiveness of the firm’s substitution possibilities between restricted and unrestricted netputs when the number of quantity controls in the background changes and gives insight into how many netputs to regulate. This local Le Chatelier effect for $\widehat{\pi}_{PK}$ and $\widehat{\gamma}_{YK}$ in (12) when removing or adding a quantity control L evaluated at $L^*(P,Q,K)$ is determined by $\widehat{\pi}_{PK}\left[P,L^*(P,Q,K),K\right]-\pi_{PK}[P,L,K]\geq 0$, where $K/\widehat{\pi}_P$ is a scaling factor for $\widehat{\gamma}_{YK}$. This difference is:

$$\widehat{\pi}_{PK}-\pi_{PK}=-\widehat{\pi}_{PL}[\widehat{\pi}_{LL}]^{-1}\widehat{\pi}_{LK}. \tag{13}$$

The expansion effect $-\widehat{\pi}_{PL}[\widehat{\pi}_{LL}]^{-1}\widehat{\pi}_{LK}$ determines whether or not the Le Chatelier effect for variable netput Y and therefore $\widehat{\gamma}_{YK}$ actually holds. When it fails, i.e. $\widehat{\pi}_{PK}-\pi_{PK}<0$, the firm's responsiveness under the regulatory regime can expand. The Le Chatelier effect for $\widehat{\pi}_{YK}$ in (13), and hence potential for sign reversal of $\widehat{\gamma}_{YK}$ in (12), depends on whether Y, K, and L are inputs or outputs and on their pattern of p- and q- substitution and complementarity, as summarized by:

Proposition 16. The local Le Chatelier effect for the elasticity of intensity when removing or adding quantity controls measures increases or decreases in responsiveness of the firm's gross substitution or complementarity possibilities between unregulated netputs and quantity controls that remain fixed. The local Le Chatelier effect for the elasticity of intensity may fail or the substitution and complementarity between unregulated and regulated netputs can reverse, depending on whether Y, K, and L are inputs or outputs and their pattern of p- and q- substitution and complementarity.

The impact upon the gross elasticity of intensity between an always unregulated netput $\widehat{Y}[P,L,K]$ and quantity control always fixed K when adding or dropping quantity control L was just considered, but what about the elasticity of intensity between the always fixed K and the quantity control that is dropped L and becomes a variable netput? This elasticity between K and freely variable L evaluated at $L^*(P,Q,K)$ is $\widehat{\gamma}_{LK}=L_{\widehat{\psi}}\widehat{\psi}_K\left[\frac{K}{L}\right]$, or:

$$\widehat{\gamma}_{LK}=[\widehat{\pi}_{LL}]^{-1}\widehat{\pi}_{LK}\left[\frac{K}{L}\right], \tag{14}$$

where $\psi=Q$ when evaluated at $L^*(P,Q,K)$. Proposition 17 summarizes the impact:

Proposition 17. Substitution (complementarity) between fixed quantity control K and formerly constrained quantity control L that is now a variable netput evaluated at its virtual quantity depends on q-complementarity (q-substitutability) between L and K when both are either fixed inputs or outputs.

[19] This section compares $\pi_{PK}\left[P,L^*(P,Q,K),K\right]$ with $P_{PK}[P,L,K]$ rather than with $\pi_{PK}[P,Q,K]$, using the equivalence of the virtual quantity with the partial static equilibrium level of the netput.

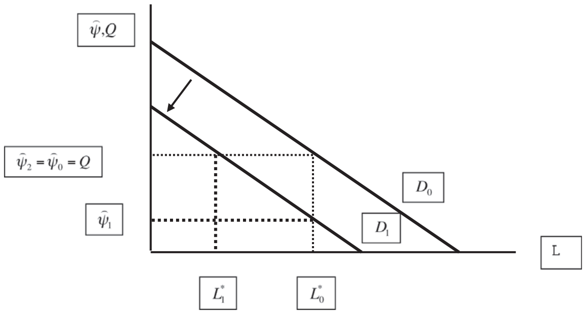

Fig. 2. Decomposition of elasticity of intensity with variable labor for q-substitution.

Decomposition of the gross elasticity of intensity

Decomposing the gross elasticity of intensity improves the regulator's understanding of firm responses to changes in quantity controls. The gross elasticity of intensity $\hat{\gamma}_{LK}$ in (14), when L is variable and evaluated at $L^*(P, Q, K)$, can be decomposed into two terms, an inverse substitution effect $\hat{\pi}_{LK}$ and an own effect $[\hat{\pi}_{LL}]^{-1}$. In words, the change in quantity of K affects the quantity of the variable netput L in two different ways. First, $\hat{\pi}_{LK}$ denotes a change in the implicit marginal valuation for L from a change in K. When L and K are q-complements (q-substitutes), $\hat{\pi}_{LK} > (<)0$, and the inverse derived demand for L shifts out (in) with an increase in K. This increase (decrease) in inverse quantity demanded for L, when L and K are q-complements (q-substitutes), increases (decreases) output(s) when there is quasi-concavity in L. Second, this change in marginal valuation induces a movement along the inverse derived demand curve for L, indicated by $[\hat{\pi}_{LL}]^{-1} \le 0$ with quasi-concavity. The more inelastic is the inverse derived demand for L, the stronger is the effect on $\hat{\gamma}_{LK}$.[20]

Empirical application

This section empirically applies the virtual quantity framework to the purse seine fishery off Peninsular Malaysia's east coast in the South China Sea.[21] Public regulation of common resources often proceeds by holding one or more inputs fixed to limit production, beginning with license limitation programs that restrict the number of firms and then moving to command-and-control restrictions on usage of individual inputs on the firm when regulators find that the first set of restrictions does not work as hoped (Squires, 1987; Dupont, 1991). Program success depends on whether firms respond to regulations by substituting unrestricted inputs for the quantity-controlled inputs to increase catches, which might then require additional quantity controls, or whether complementarity prevails that allows restricting only key inputs. Along Peninsular Malaysia's east coast, a license limitation program on commercial purse seiners limits the number of vessels but places no further restrictions upon vessel size or the harvest function.

Empirical model

The model of a fishing trip specifies capital (K), the vessel (measured by its length), as a fixed factor. Labor ($L < 0$), the number of crewmembers (including captain), may be quasi-fixed if it is fixed over the production period but variable and chosen optimally over a longer time period, with price P''_L, where " denotes a nominal price that is not yet normalized.[22] Fuel ($Y_F < 0$) is a variable input with price P''_F. Other variable inputs such as ice are minimal, are predetermined prior to the trip, and do not vary, since a constant amount is used on a trip. Thus, they can be viewed as Leontief separability.

The restricted profit function with vessel K fixed and labor L potentially quasi-fixed, is: $\pi'' = \pi''\left[P''_Y, P''_F, L, K\right]$, where P''_Y is the price of fish ($Y > 0$). Restricted profit for a fishing trip π'' is total revenue less variable fuel's cost. The normalized quadratic profit function is (Lau, 1976):

$$\pi[P_F, L, K] = \alpha_0 + \sum\nolimits_{r=1,2} \alpha_r D_r + \alpha_F P_F + \alpha_K K + \alpha_L L + \sum\nolimits_{r=1,2} \alpha_{rF} D_r P_F + \sum\nolimits_{r=1,2} \alpha_{rK} D_r K + \alpha_{FF} P_F^2 + \alpha_{KK} K^2 + \alpha_{LL} L^2 + \alpha_{FK} P_F K + \alpha_{FL} P_F L + \alpha_{LK} LK, \tag{15}$$

where $\pi[P_F, L, K] = \frac{\pi''}{P''_{Y,}} = P_F = \frac{P''_F}{P''_Y}$ and symmetry is imposed. Linear homogeneity in prices requires $\alpha_Y = 1 - \alpha_F, \alpha_{YY} = \alpha_{FF}$, $\alpha_{YF} = -\alpha_{FF}.\alpha_{YK} = -\alpha_{FK}, \alpha_{YL} = -\alpha_{FL}$ $\alpha_{1F} = -\alpha_{2F}$ and $\alpha_{1K} = -\alpha_{2K}$. Dummy variables D_r are specified for vessels with high catches (catch > 10,000 kg), D_1, and for adoption of embodied mechanical and electronic process innovations (net hauler,

[20] Fig. 2 illustrates the decomposition of $\hat{\gamma}_{LK}$ from (14) for q-substitution ($\frac{\partial \psi}{\partial L} < 0$) and $0 < L < L^*$.

[21] Purse seine nets encompass schools of pelagic fish (fish in the water column not bottom).

[22] Labor is initially specified as quasi-fixed to allow for labor market imperfections and time to adjust in response to market forces. Imperfect labor markets may be due to custom and social norms, extended family and other long-term relationships, and difficulties in transferring out of the specialized fishing labor market.

GPS, radio, echo sounder, sonar), D_2. D_1 captures spatial variation of homeports (high catch is found only in certain southernmost ports), resource abundance and availability along the coast, and trip length and duration (much longer for high catches). D_2 is specified as quasi-fixed. The cross-section data pertain to one fishing trip, giving constant resource abundance.

The variable netput demand equation for fuel is given by Hotelling's Lemma:

$$\frac{\partial \pi[P_F, L, K]}{\partial P_F} = -Y_F(P_F, L, K) = \alpha_F + \sum\nolimits_r \alpha_r D_r + \alpha_{FF} P_F + \alpha_{FK} K + \alpha_{FL} L. \tag{16}$$

Equality of parameters between (15) and (16) is maintained. The supply equation for catch is derived from the econometric restrictions for linear homogeneity in prices. Online Appendix B derives the equations presented below plus additional equations.

The explicit form of the virtual quantity of labor, $L^*[P_F, P_L, K]$, given implicitly in (1) is:

$$L^*[P_F, P_L, K] = \frac{1}{\alpha_{LL}}[P_L - \alpha_L - \alpha_{FL} P_F - \alpha_{LK} K]. \tag{17}$$

The shadow price of fixed K evaluated at $L^*[P_F, P_L, K]$, $\widehat{\omega} = \widehat{\pi}_K\left[P, L^*, K\right]$ from (2), is:

$$\widehat{\omega} = \widehat{\pi}_K\left[P_F, L^*, K\right] = \alpha_K + \frac{\alpha_{LK}}{\alpha_{LL}}[P_L - \alpha_L] + \left[\alpha_{FK} - \frac{\alpha_{LK}\alpha_{FL}}{\alpha_{LL}}\right] P_F + \left[\alpha_{KK} - \frac{\alpha_{LK}^2}{\alpha_{LL}}\right] K. \tag{18}$$

The local Le Chatelier effect on capital's shadow price for own changes in capital when lifting the quantity control on L, evaluated at the virtual quantity (17) and corresponding to (6), is:

$$\widehat{\pi}_{KK} - \pi_{KK} = -\widehat{\pi}_{KL}[\widehat{\pi}_{LL}]^{-1}\widehat{\pi}_{KL} = -\frac{\alpha_{LK}^2}{\alpha_{LL}}. \tag{19}$$

The net elasticity of intensity between the variable netput fuel consumption Y_F ($Y_F < 0$) and the fixed netput vessel length, K, with labor L fixed, corresponding to (11), is:

$$\gamma_{FK} = \frac{\partial \ln Y_F}{\partial \ln K} = \alpha_{FF}\frac{K}{Y_F}. \tag{20}$$

Table 1
Summary statistics of the data per vessel per fishing trip.

Variable	Unit	Mean	Standard deviation	Minimum	Maximum
Short-Run Profit	RM	4409.97	6828.53	39.20	34,400.00
Revenue	RM	5230.64	7906.51	140.00	40,000.00
Trip duration	Hours	26.72	25.19	2.00	124.00
Trip distance	Kilometers	24.37	38.39	1.80	250.00
No. hauls of net	Hauls per Trip	4.30	3.54	1.00	20.00
Vessel length	Meters	17.23	5.79	5.20	36.00
Vessel volume	GRT	28.67	18.88	11.00	100.00
Engine power	Horsepower	215.96	297.36	11.00	1500.00
Mesh size	Inches	87.75	0.54	0.75	3.75
Quantity of:					
Catch	Kilograms	3143.43	6141.74	70.00	30,000.00
Fuel	Liters	616.92	972.62	15.00	4000.00
Labor	Persons	17.32	7.97	5.00	40.00
Net length	Meters	473.55	225.42	88.00	1000.00
Price of:					
Catch	RM per kg	2.78	2.39	0.60	15.00
Fuel	RM per liter	1.33	0.18	0.67	1.60
Labor	RM per person	2601.86	3777.62	1.00	12,987.00
Net	RM per meter	20.04	20.89	0.25	135.83
Frequency of:		Percent	Mean year adopted		
Process innovation	Percent	83.33			
Mechanical: Net hauler	Percent	48.15	1995		
Electronics	Percent	77.78			
GPS	Percent	57.41	1994		
Radio	Percent	24.07	2002		
Echo sounder	Percent	57.41	1999		
Sonar	Percent	12.96	2002		

Number of observations = 60. Values are in 2006 Malaysian Ringgit (RM). Short-run trip profits are total revenue less fuel cost. Process innovation entails all process innovations, electronics entails all innovations except the mechanical net hauler. Labor includes captain, mechanic, and crew.

Table 2
Hypothesis tests of profit function specification.

Null hypothesis	χ^2	No. of independent restrictions	p-Value	Reject H_0? (Y/N)
Dummy variables for large catch and innovations vs. no dummy variables	114.63 (6.85)	6	0.00 (0.34)	Y (N)
Dummy variables for innovations vs. no dummy variable for innovations	6.78 (1.49)	3	0.08 (0.69)	N (N)
Dummy variables for large catch vs. no dummy variables	(5.36)	(3)	(0.15)	(N)

Note: Likelihood ratio from ML estimation tests are presented without parentheses and distance tests from GMM estimation presented in parentheses. All dummy variables affect intercept of restricted profit function. Process innovations include mechanical (net hauler) and electronics. Large catch is catch > 10,000 kg. Variable input is diesel fuel consumption and quasi-fixed inputs are labor (crew size) and capital (vessel length). Two-step systems generalized methods of moments with instrumental variables allows for endogenous catch dummy and labor and maximum likelihood estimation specifies exogenous catch dummy and labor.

Net elasticity of intensity between fuel Y_F and fixed L with K fixed, corresponding to (11), is:

$$\gamma_{FL} = \frac{\partial \ln Y_F}{\partial \ln L} = \alpha_{FL}\frac{L}{Y_F}. \tag{21}$$

$\gamma_{FK} > (<)0$ when Y_F and K are p-complements (substitutes) and the same holds for γ_{FL}.

The gross elasticity of intensity between variable $\widehat{Y}_F$ and fixed K when removing or adjusting L evaluated at $L^*[P_F, P_L, K]$ and corresponding to (12), is:

$$\widehat{\gamma}_{FK} = \frac{\partial \ln \widehat{Y}_F}{\partial \ln K} = \frac{\partial^2 \widehat{\pi}_{P_F K}\left[P_F, L^*(P_F, P_L, K), K\right]}{\partial P_F \partial K}\frac{K}{\widehat{Y}_F} = \left[\alpha_{FK} - \frac{\alpha_{FL}\alpha_{LK}}{\alpha_{LL}}\right]\frac{K}{\widehat{Y}_F}, \tag{22}$$

where $\widehat{\gamma}_{FK} > (<)0$ as Y_F and K are p-complements (-substitutes). Corresponding to *Decomposition of the gross elasticity of intensity*, the pure substitution effect is α_{FK} and the expansion effect is $\frac{\alpha_{FL}\alpha_{LK}}{\alpha_{LL}}$.

The Le Chatelier effect on responsiveness of fuel demand $\widehat{Y}_F$ to changes in K when adjusting or removing L, evaluated at $L^*[P_F, P_L, K]$ and corresponding to (13), also gives the Le Chatelier effect for $\widehat{\gamma}_{YK}$ in (12) when scaled by $\frac{K}{\widehat{\pi}_P}$, and is specified as:

$$\widehat{\pi}_{FK} - \pi_{FK} = -\widehat{\pi}_{PL}[\widehat{\pi}_{LL}]^{-1}\widehat{\pi}_{LK} = -\frac{[\alpha_{FL}\alpha_{LK}]}{\alpha_{LL}}. \tag{23}$$

The gross elasticity of intensity between formerly fixed and now variable input L and fixed K, $\widehat{\gamma}_{LK} = \frac{\partial \ln L}{\partial \ln K} = \widehat{\pi}_{LK}[\widehat{\pi}_{LL}]^{-1}\left[\frac{K}{L}\right]$, evaluated at $L^*[P_F, P_L, K]$ and corresponding to (14), is:

$$\widehat{\gamma}_{LK} = -\frac{\alpha_{LK}}{\alpha_{LL}}\left[\frac{K}{L}\right], \tag{24}$$

where $\widehat{\gamma}_{LK} > (<)0$ as L and K are q-substitutes (-complements) or p-complements (-substitutes).

Data and estimation

The 2006 cross-sectional data are from direct surveys of fishing vessel owners or captains conducted by the World Fish Center in the Malaysian states of Kelantan, Terengganu, and Kuantan on the east coast of Peninsular Malaysia. The data were collected according to a stratified random sample, as discussed in online Appendix C, giving disturbances for (15) and (16) that are independent but not identically distributed over vessels (i.e. the distribution is independent but can vary over vessels, inid). Table 1 summarizes the data and online Appendix C provides further discussion.

The normalized quadratic restricted profit function, (15), and the variable factor demand equation for fuel and oil use, (16), with cross-equation and symmetry constraints imposed, were initially jointly estimated by maximum likelihood (ML) with heteroscedastic-consistent errors (White, 1980) and additive disturbances for each equation. The model was also estimated by two-step (optimal) systems generalized method of moments using instrumental variables (IV), denoted GMM, to allow and test for potential endogeneity of the catch dummy and labor variables, again with robust standard errors that are asymptotically efficiently and normally distributed.[23]

[23] An anonymous referee noted potential endogeneity of the technology dummy variable D_2 (if embodied technology is not quasi-fixed), the catch dummy variable, D_1, and quasi-fixed labor. Identification for embodied technology ideally requires information on social networks (Conley and Udry, 2010), equipment prices, opportunity costs of labor outside of the fishing sector in the vicinity of the fishing villages or ports (just rivers or their mouths), and ideally panel or pseudo-panel data to account for time to adopt process innovations. Identification of D_2 is not possible because these data are unavailable, but potential endogeneity rather than exogeneity and quasi-fixity of embodied technology, and hence inconsistent parameter estimates, is noted. Identification of D_1 and L in (15) and (16) uses all exogenous variables (including constant) in (16) plus both (15) and (16) use survey data for normalized net price, and dummy variables for owner-operatorship and the two southernmost home districts combined (Besut and Pasir Puteh) to account for greater distance from shore, larger and more expensive nets, greater quantity of labor required to catch and haul in larger catches, differences in skippers or tenure driving searches for larger catches, proximity to larger markets (Kuala Lumpur and Singapore) that can absorb larger catches, and potential spatial differences in resource abundance. Additional instruments include mesh size, horsepower, net length, and price of catch. Because the opportunity cost of

Table 3
Final parameter estimates for normalized quadratic restricted profit function for purse seine production in Malaysia.

Parameter	Maximum likelihood	Generalized method of moments with both catch dummy and labor variables endogenous
α_0	−7091.00** (1699.12)	1383.01 (4454.71)
α_D	2314.71 (7916.15)	
α_Y	−799.60** (291.97)	−681.32** (156.13)
α_F	800.56** (226.32)	682.32** (156.13)
α_L	472.83** (126.73)	411.31 (355.92)
α_K	387.44* (147.17)	−716.33 (470.25)
α_{YD}	1451.01** (561.11)	
α_{YY}	201.76* (94.59)	361.91** (56.91)
α_{YF}	−201.76* (94.59)	−361.91** (94.59)
α_{YL}	60.63** (13.33)	57.50** (13.81)
α_{YK}	23.81 (18.62)	27.97 (15.92)
α_{FD}	−1451.01** (305.83)	
α_{FF}	201.76** (66.15)	361.91** (56.91)
α_{FL}	−60.63** (11.74)	−57.50** (13.82)
α_{FK}	−23.81 (15.33)	−27.97 (15.92)
α_{LL}	8.02* (4.02)	−47.92** (13.57)
α_{LK}	−29.92** (7.70)	90.68** (34.63)
$\alpha_{KD}\pi_{ij}$	658.75** (305.83)	
α_{KK}	2.79 (3.81)	

Note: Heteroscedastic-consistent (robust) standard error in parentheses.
D denotes large catch (> 10,000 kg) dummy variable, Y denotes catch (output), F denotes fuel (variable input), L denotes labor (number of crew, quasi-fixed factor), K denotes capital (vessel length, fixed factor).
Catch equation parameters derived from linear homogeneity and symmetry restrictions, with linearized standard errors by delta method.
* Denotes statistically significant at 5%.
** Denotes statistically significant at 1%.

Table 4A
Price and shadow price elasticities, maximum likelihood estimation.

	Quantity		Shadow price		
Change in price of:	Output (Catch)	Fuel	Labor	Capital	Capital at virtual quantity of labor
Output (catch)	0.033 * (0.016)	0.236* (0.110)			
Fuel	−0.033 * (0.016)	−0.236 * (0.110)			
Change in quantity of:					
Labor			0.948 (2.039)	1.869 (1.164)	
Capital			−3.516 (6.478)	−0.174 (0.109)	0.391** (0.089)

Note: Dependent variable given by column headings. Estimated at arithmetic mean of data.
Robust standard errors in parentheses.
Own change capital at virtual quantity of labor is statistically insignificant, but its elasticity is positive and statistically significant.
* Denote statistically significant at 0.05.
** Denote statistically significant at 0.01.

Table 4b
Price and shadow price elasticities, generalized method of moments estimation.

Change in price of:	Quantity Output (Catch)	Fuel	Shadow price Labor	Capital	Capital at virtual quantity of labor
Output (catch)	0.060** (0.010)	0.422** (0.066)			
Fuel	−0.060* (0.010)	−0.422** (0.066)			
Change in quantity of:					
Labor			−0.271** (0.042)	1.067** (0.394)	
Capital			0.510** (0.145)	−0.065 (0.053)	0.711** (0.238)

Note: Both catch dummy variable and quantity of labor endogenous.
Dependent variable given by column headings. Estimated at arithmetic mean of data.
Robust standard errors in parentheses.
Own change capital at virtual quantity of labor is statistically insignificant, but its elasticity is positive and statistically significant.
* Denote statistically significant at 0.05.
** Denote statistically significant at 0.01.

Table 5A
Elasticities of intensity, maximum likelihood estimation.

Change in quantity of:	Fuel (with fixed labor)	Fuel (with virtual quantity of labor)	Virtual quantity of labor
Labor	1.702** (0.347)		
Capital	0.665 (0.520)	−0.027 (0.024)	5.088 * (2.103)

Note: Dependent variable given by column headings. Estimated at arithmetic mean of data.
Standard errors in parentheses.
* Denote statistically significant at 0.05.
** Denote statistically significant at 0.01.

Empirical results

A Hausman test comparing ML and GMM estimates for the initial, full model indicates that GMM is appropriate for evaluating model structure vis-à-vis dummy variables.[24, 25] GMM distance tests (Newey and West, 1987) indicated that neither dummy variable belonged in the model whereas ML likelihood ratio tests indicate a final model comprised of D_1 (Table 2). The GMM distance test of both dummy variables versus no dummy variables was rejected. Further distance testing of first D_2 and then subject to its exclusion, distance testing of D_1 confirmed exclusion of both yielded convincing evidence for exclusion of both D_1 and D_2.[26] The same qualitative results were obtained with both ML and GMM when electronic and mechanical innovations were separately evaluated. The ML likelihood ratio test indicates that vessels with $D_1>0$ had higher catches (as expected), lower fuel consumption, and larger vessel sizes but not higher profits than vessels with $D_1=0$.

ML and GMM parameter values of the final models are reported in Table 3. The generalized R^2 for the entire system of equations for ML is 0.945, and the R^2values are 0.81 (0.15) for the restricted profit Eq. (15) and 0.70 (0.53) for the fuel Eq. (16), where the final GMM results (with endogenous L, no D_1 or D_2) are given in parenthesis or second throughout the paper. The statistically significant and highly inelastic Marshallian own price elasticities for output supply and fuel demand for both ML and GMM reflect the short time period of a fishing trip (Tables 4a and b).[27]

The local Le Chatelier effect on the shadow value of K, (6) and (18) and evaluated at $L^*[P_F, P_L, K]$ from (17), fails to hold for ML but marginally fails to hold for GMM with rejection (nonrejection) of H_0: $-\frac{\alpha_{LK}^2}{\alpha_{LL}} = -111.57\ (171.58) \geq 0$ (one-sided p-

(*footnote continued*)
labor (to form the basis for a shadow wage rate), whether in kind or cash, was unavailable (which would have required a sample of nearby non-fishing occupations, which was beyond the survey budget and intent), the use of IVs from the survey was required. The choice was made to error on the side of multiple potentially weak instruments for L (same in both equations) for consistent estimates, recognizing the potential impact upon small sample bias (worsens) and asymptotic efficiency (improves). GMM estimation also addresses potentially biased and inconsistent parameter estimates due to measurement error with recall data. The large number of df largely comes from (16). Greater asymptotic efficiency is obtained with more IVs, leading to including the same IVs in both equations.

[24] The Hausman test value of the full model (both dummy variables), distributed chi-square with df=5, χ_5^2, was 26.29 (upper tail area of 0.00003), indicating rejection of the null hypothesis of exogenous D_1 (conditional upon exogenous D_2) and L, indicating ML is inappropriate. The test value of the Sargan–Hansen overidentifying restrictions (OIR) test for the GMM model with both D_1 and L endogenous (conditional upon exogenous D_2), distributed as χ_{14}^2 (df=number of OIR), was 10.71 (p-value=0.708), indicating non-rejection of the null hypothesis that the instruments are distributed independently of the error process and indicating suitability of the instruments. In addition, A Hausman test comparing ML and GMM estimates for the initial, full model indicates that GMM is appropriate for evaluating model structure vis-à-vis dummy variables. Because of the poor power properties of the Hausman pretest (Guggenberger, 2010a, 2010b), both ML and GMM results are retained. Both the ML and preferred GMM estimation give similar results for most of the key measures of interest, notably the elasticities of intensity.

[25] Multicollinearity issues precluded interacting D_1 and D_2 with both K and L in the initial, full model. Reestimating the model with both D_1 and D_2 interacting with L rather than K gave the same qualitative results for the Hausman, likelihood ratio, and GMM distance tests, tests of convexity and quasi-concavity, and elasticities for price and intensity.

[26] The GMM distance test is (Newey and West, 1987): $D=n(Q_0\text{-}Q_1)$, where Q_0 is the value of the minimum distance criterion for the null hypothesis (restricted) (H_0), Q_1 is the value without H_0 (unrestricted) (H_1), and n is the number of observations. D is distributed chi-square with df=number of restrictions. Because D can be ill behaved (have the wrong sign), the hypothesis testing imposes a constant asymptotic variance-covariance matrix **S** (and hence constant weighting matrix **W**) across the unrestricted (H_0) and restricted (H_1) estimators. Since the unrestricted estimator is consistent across both H_0 and H_1, a consistent, unrestricted GMM estimator is used to estimate **W,** thereby insuring $D \geq 0$.

[27] The price elasticities (see online Appendix B for formulae) satisfy the necessary conditions for a well-behaved restricted profit function. With only a single normalized price for the single variable netput (fuel), the sufficient condition for convexity in prices is automatically satisfied. The (weak) monotonicity conditions for the inverse derived demand equations are satisfied at the sample mean with non-rejection of H_0:$\pi_L=\psi=146.56(3064.09)\geq 0$ (one-sided p-values=0.272/0.000) and H_0:$\pi_K=\omega=-99.69(4653.24)\geq 0$ (one-sided p-values=0.173/0.000) for ML and GMM, respectively. $\omega<0$ for 14 of 60 observations and $\psi>0$ for all 60 observations. The necessary conditions for quasi-concavity are satisfied except for L under ML and completely for GMM:$\alpha_{LL}=(8.02\,/-47.92)$ (one-sided p-values=0.023/0.000) and $\alpha_{KK}=(2.79/-17.67)$ (one-sided p-values=0.232/0.302). Quasi-concavity is satisfied for both estimation strategies, with non-rejection of H_0:$\alpha_{LL}\alpha_{KK}-\alpha_{LK}^2=-872.76(-7375.9)\leq 0$ (one-sided p-values=0.035/0.193). Quasi-concavity of the restricted profit function with respect to K, corresponding to (8), is satisfied when L is variable and evaluated at $L^*(P,Q,K)$, with non-rejection of H_0:$\widehat{\pi}_{KK}=\alpha_{KK}-\frac{\alpha_{LK}^2}{\alpha_{LL}}=40.67(6.076)\leq 0$ (one-sided p-values=0.461/0.197). $\pi_K[P,L,K]=\omega=$ 4653.24 (p-value=0.000) and $\pi_L[P,L,K]=\psi=$ 3064.09 (p-value = 0.000). The virtual quantity of labor, $L^*(P,Q,K)$, is 40.01 (p-value=0.000) and $L^*(P,L,K)>0$ for all observations. The mean shadow price of capital evaluated at, $L^*(P,Q,K)$, is $\widehat{\pi}_K\left[P,L^*(P,Q,K),K\right]=\widehat{\omega}=3781.33$ (p-value=0.000). $\widehat{\omega}>0$ for all sample values, which when contrasted with some $\omega<0$ indicates that some vessels were making losses due to suboptimal crew sizes. $\widehat{\omega}>\omega$ due to profit maximization when L becomes variable and crew size becomes optimized.

Table 5B
Elasticities of intensity, generalized method of moments estimation

Change in quantity of:	Fuel (with fixed labor)	Fuel (with virtual quantity of labor)	Virtual quantity of labor
Labor	1.614** (0.388)		
Capital	0.781 (0.445)	0.009** (0.002)	2.582** (0.512)

Note: Qquantity of labor endogenous.
Dependent variable given by column headings. Estimated at arithmetic mean of data.
Robust standard errors in parentheses.
** Denote statistically significant at 0.01.

values = 0.009/0.063). Easing the regulatory regime fails to loosen the responsiveness of inverse derived demand and the unit rent for quantity control K with variable L under ML.[28]

Consider potential firm response to input quantity controls by substituting unrestricted for restricted inputs. The statistically significant net elasticity of intensity between (quasi-fixed) L and variable fuel with fixed K from (11) and (20) is $\gamma_{FL} = 1.70(1.61)$ (Tables 5a and b), indicating p-complementarity between L and fuel. Fuel is representative of trip length, which in turn represents choice of fishing grounds, species to target, etc. The elastic complementary values for γ_{FL} indicate no scope for vessels to respond to any restrictions on labor (e.g. imposed as part of a license limitation program to conserve common resource stocks) by fishing longer and thereby placing additional pressures on resource stocks. Instead, fixing or reducing crew size lowers fuel consumption and trip length and thereby lowering catches with very labor-intensive purse seining. The statistically insignificant net elasticity of intensity between K and variable fuel with L fixed from (11) and (20) of $\gamma_{FK} = 0.66\ (0.78)$ (Tables 5a and b) indicates no p-substitution or p-complementarity. The absence of substitutability means that vessels cannot respond to restrictions on vessel size, which are common to license limitation programs, by substituting unrestricted fuel (and thereby fishing longer) for restricted K. The absence of complementarity means that the regulator has no scope to limit time on the water and hence catch through restricting vessel size in the short run when L is quasi-fixed.

Setting an additional quantity control, or conversely relaxing a quantity control, further binds or loosens the firm's ability to respond to remaining quantity controls. Consider relaxing fixed L to its virtual quantity value $L^*[P_F, P_L, K] = 40.01$ (p-value = 0.000), so that it becomes a variable input at its profit-maximizing level. For example, one property rights approach to the commons problem establishes an overall industry input quota and transferable licenses for that input, creating an ITE program, which could be built around an input formerly regulated by quantity controls, here simply for illustration purposes, labor.

The gross elasticity of intensity between fuel and vessel length with unregulated and variable labor evaluated at $L^*(P_F, P_L, K)$, $\widehat{\gamma}_{YK}$ in (12) and (22), gauges the gross substitution possibilities between fuel and vessel length. The statistically insignificant (significant) elasticity values of -0.027 (0.009) (Tables 5a and b) indicate neither gross p-substitution nor p-complementarity under ML but highly limited p-complementarity under the preferred GMM. Firms respond to removing the quantity control L by increasing fuel consumption and thus fishing time and presumably catch. Nonetheless, the elasticity, while significant, is so close to zero that the firm response can be practically viewed as negligible.

Does (gross) $\widehat{\gamma}_{YK}$ tighten up, loosen, or even reverse sign compared to (net) γ_{YK} when removing or adding a quantity control L? The term in the local Le Chatelier effect $\widehat{\pi}_{FK} - \pi_{FK}$ in (13) and (23), which gives the Le Chatelier effect for $\widehat{\gamma}_{YK}$ when scaled by $\frac{K}{\pi_P}$, is 253.69 (147.76) (one-sided p-values = 0.369/0.287), indicating that the Le Chatelier effect holds with variable L (since it is non-negative). If statistically significant, the sign reversal for $\widehat{\gamma}_{YK}$ from γ_{YK} would suggest both altered and expanded scope for the firm to respond to tightening limits on K when the larger crew sizes under variable L allow handling more fish. The sign change would indicate reversal in the firm's substitution possibilities between K and fuel from net complementarity to gross substitutability, so that limiting vessel length say in a license limitation program can lead vessels to burn more fuel by fishing longer to catch more fish and thereby evade the intent of the length limitation.

The potential for gross substitution between fixed K and variable L (evaluated at $L^*(P_F, P_L, K)$) is given by $\widehat{\gamma}_{LK}$, (14) and (24). The statistically significant $\widehat{\gamma}_{LK}$, evaluated at $L^*(P_F, P_L, K)$, is 5.09 (2.58) (Tables 5a, b), with the large and significant positive value indicating strong gross p-complementarity between K and variable L with both ML and with GMM. The large values under ML and GMM are due to a gross q-substitution effect between K and L that is much stronger than the own effect for L (see (14)). A larger crew on a larger vessel hauls up a larger net loaded with more fish and more quickly processes this catch for the labor-intensive harvesting process. The key relevant point is that no gross p-substitution possibilities exist under either estimation strategy when crew size becomes variable over a longer time period than the fishing trip considered. Should the regulator impose a vessel size limit under a license limitation program, firms would not be able to respond by increasing crew size in an attempt to catch more fish and counter the vessel size limit.

[28] Moreover, $\pi_K[P, L, K] \geq 0$ and $\widehat{\pi}_{KK}\left[P, L^* K\right] > \pi_{KK}[P, Q, K]$ from (6), but $\widehat{\pi}_{KK}\left[P, L^*(P, Q, K), K\right] = \widehat{\omega}_K = \alpha_{KK} - \frac{\alpha_{LK}^2}{\alpha_{LL}} = 153.92 > 0$, even though $\pi_{KK}[P, Q, K] = \alpha_{KK} \leq 0$. However, $\widehat{\pi}_{KK}\left[P, L^*(P, Q, K), K\right] > 0$ is marginally statistically insignificant (p-value = 0.062), but its elasticity value is statistically significant (Tables 4a and b).

Finally, consider a transferable rights program, denominated in perfectly divisible units of vessel length, which limits the total industry vessel size and allows rights trade and vessel length replacement.[29] Such a program may be preferred to transferable catch rights in a developing or middle-income country with complex multispecies fisheries due to easier and cheaper monitoring and enforcement plus difficulties in assessing populations and sustainable target catches (Alam et al., 2002). Such a program may also be preferred to a transferable effort (days at sea or fished) right, also due to monitoring and enforcement issues and difficulties in estimating populations and Total Allowable Effort. To calculate the potential quasi-rent that could be generated under full information, no transactions costs, effective monitoring and enforcement, and full divisibility, evaluate the estimate of $\sum_m \widehat{\pi}_K\left[P, L^*(P,Q,K), K\right] = \widehat{\omega}$ at $\overline{K}$, here arbitrarily set for purposes of illustration at $\theta \sum_m^M K_m = \overline{K}$, $0 < \theta < 1$.[30] Online supplementary Appendix E provides formulae for all calculations.

Concluding remarks

The virtual quantity framework allows positive analysis of individual competitive multiproduct firm behavior under existing multiple quantity controls to better design public regulation. These quantity controls can be fixed by command-and-control regulations or transferable as property rights in cap-and-trade systems, but quasi-fixed during a production period, fixed by firms, or fixed as primary endowments, public goods (or bads), or common resources. The approach allows regulators to anticipate firm behavior for changes in command-and-control quantity control systems and in the transition from command-and-control quantity controls to systems of transferable property rights with secondary markets. This *ex post* approach is dual to the *ex ante* virtual price framework. When the virtual quantity framework reveals considerable scope for firms to react to regulations in unexpected or undesired ways, either the regulatory approach requires rethinking or additional monitoring and enforcement are required.

Several unique results fall out of the virtual quantity framework. First, fishers' unanticipated reactions to quantity controls are not (necessarily) due to a deliberate intention to evade or not follow the regulations, but because the technology combined with regulatory design and market conditions induce their rational response. Second, caution may be warranted on the number and/or choice of outputs or inputs that are subject to quantity controls due to the growing complexity and uncertainty of firm responses and due to possible failure of quasi-concavity, which in turn can lead to perverse investment decisions and unstable secondary markets for transferable rights in cap-and-trade systems. Third, when adding or removing quantity controls, the ability of firms to evade quantity controls through substituting unrestricted netputs for quantity controls can even reverse, catching the regulator off guard, depending on the number of other binding quantity controls and their substitution possibilities. Fourth, when adding or removing quantity controls, the responsiveness or Le Chatelier effect for substitution or complementary between unregulated and regulated netputs can fail. Fifth, when the Le Chatelier effect does hold as expected, adding quantity controls strengthens local Le Chatelier effects that increasingly bind firm behavior, shrinking profits and limiting firm flexibility response to changing markets and environment. In multispecies fisheries, the Le Chatelier effects from adding quantity controls on catches can have detrimental impacts through overexploiting fish stocks when matching catches with quantity controls. Nonetheless, transferable rights, fisher responses, and programs to handle quantity control imbalances and overages can alleviate many of the otherwise cramping influences on firm flexibility (Squires et al., 1995; Sanchirico et al., 2006; Miller and Deacon, 2014).

The virtual quantity framework applied to a Malaysian fishery regulated by license limitation demonstrates no potential for firms to circumvent command-and-control quantity controls on inputs aimed at achieving sustainable use of the fishery. The pervasive input complementarity instead points to quantity controls that can lower harvest pressures on the common resource stock. Instituting a transferable property right on vessel size with a cap-and-trade secondary market has the potential for sizeable welfare gains due to the introduction of the transferable right and subsequent arbitrage efficiency.

Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.jeem.2015.04.005.

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[29] There is precedence. The Inter-American Tropical Tuna Commission's capacity management program (established under Resolution C2-03) established a similar program through limited cubic meters of well capacity. Deacon et al. (2011) Fig. 1 illustrates a related analysis under conditions of homothetic input separability (allowing a consistent composite input index, effort), complete divisibility, and no transactions and information costs.

[30] Unfortunately, the empirical results do not allow calculation (see online Appendix E for how), even though first- and second-order conditions are satisfied as discussed above. However, although not statistically violating quasi-concavity, the calculated values correspond to an upward sloping inverse derived demand curve due to the extremely large gross p-substitution between L^* and K, α_{LK}.

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