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Low, High and Super Congestion of an Open-Access Resource: Impact under Autarky and Trade, with Aquaculture as Illustration*

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Abstract

Analysis of open-access common-property natural resource (*NR*) has occurred under "low" congestion (LC) – where AC and MC increase with output Q – and has for the most part ignored the more important congestion categories where AC (MC) is backward-bending (negative) and welfare and *NR* losses are significantly greater. This paper identifies two such categories, "high" (HC) and "super" (SC) congestion, and examines the impact of open access on steady-state welfare, *NR*, employment, output and price in a general equilibrium model. Main findings are: i) Welfare and *NR* costs (and optimal taxes) are a multiple or orders of magnitude greater under HC and (especially) SC than under LC, with trade further – and always – reducing an open-access exporter's *NR* and welfare. These results are robust to alternative parameter values and functional forms and greatly increase the importance of regulation; ii) An optimal tax raises price and reduces output under autarky in the case of LC and HC but *reduces* price and *raises* output under SC, with significantly larger gains; iii) Studies conducted under LC show trade between open-access developing country C1 and regulated but otherwise identical C2 reduces C1's welfare and both C1's and global *NR*, and though the same holds under HC, the *opposite* holds under SC; iv) Trade between two open-access countries – say, a developing and an emerging one – with different externality (population) levels raises global output and welfare, improves *NR*'s global efficiency, raises (does not affect) its level, and reduces international inequality; and v) Emigration's welfare gain is much larger under SC than under LC, especially if migration results in LC after migration. Application to other issues and policy implications are provided.

Keywords: Open Access, natural resource, unexamined high congestion, autarky and trade, aquaculture
JEL codes: D62, F18, Q22, Q27, Q56

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1. Introduction

Many developing countries obtain a large share of their income from the exploitation of open-access common-property renewable natural resources (*NR*), including fisheries, forests, arable land, grazing grounds, and water resources. Imperfect or lack of property rights for the *NR* results in the partial or non-internalization of negative externalities,[1] an excessive use of labor and other variable inputs and *NR* degradation.

This problem has affected many developing countries and has led to the decline or disappearance of communities due to rapid population growth, access to a wider market, and more. For instance, Brander and Taylor (1998) argue that open access to a rich resource base led to economic growth, population overshooting and the disappearance of Easter Island's forests, with a dramatic decline in population and well-being over time.

The classic case of *NR* depletion is that of fisheries, which has affected a large number of countries over time. Early studies of *NR* depletion focused on this issue (e.g., Gordon 1954, Scott 1955). This paper selects aquaculture, or fish farming, to illustrate the problem examined as the sector's output has grown extremely rapidly in recent years – from about a third in 2005 to over 50 percent of global fish output in 2015 (FAO 2016) – and so have the associated negative externalities. The analysis is directly applicable to a number of other *NR* and non-*NR* cases (see Section 5).

Given farm fishing's recent growth, it is no surprise that most analyses to date have focused on wild fishing. Models designed to explain the evolution of the stock of wild fish (and other renewable *NR*s) have typically included equations for the stock's natural and actual growth, i.e., natural growth minus harvest.

Farmed fish requires a different model as the fish fry is produced in hatcheries and nurseries and its supply is essentially independent of fishing intensity, as is the size of the production area and water volume or *NR* quantity. On the other hand, *NR quality* declines with fishing intensity or density of variable inputs (e.g., pens, labor). Excessive farm fishing intensity

[1]For instance, López (1997, 1998) finds that the share of the negative *NR* externalities – from the use of village-level common-property lands in Ghana and Côte d'Ivoire – that is internalized is around 30 percent and declines with village size.

generates *two* types of problems, namely low quality and hence low productivity of the *NR*, and greater volatility due to the rapid spread of a negative shock to one unit (e.g., a disease) to the rest of the industry. Such problems are common in many farm fishing countries. Examples provided here draw on the industry's experience in Chile and the Philippines.

Open access and a lack of regulations has led to an excessively high density of pens in the case of Chilean salmon. This resulted in a parasite and disease outbreak in 2008. The parasite spread rapidly across the industry and destroyed two thirds of the output through 2009 and 2010. The episode led to a number of regulatory changes, though the sector has continued to be plagued by frequent problems (Anderson 2012). The excessive pen density has also led to high pollution levels and lower productivity in the industry. [2]

A similar problem has been found in various parts of the Philippines. For instance, Yambot (2000) examined tilapia farms in Lake Taal and found high congestion of fish cages, as well as high stocking density and feeding rates. These resulted in extremely high levels of ammonia and nitrogen and very low levels of dissolved oxygen, with high pollution levels and widespread waste materials, and floating dead fish abounding due to mass mortality, all of which have led to chronic disease of the surviving fish. Similar problems occurred in the coastal waters of the islands of Luzon and Mindanao. Among the most dramatic events were a series of mass mortalities of milkfish in Bolinao, Pangasinan in 2002, with water quality and habitat degraded to a degree that severely diminished the likelihood of cultured fish survival and growth (Talaue-McManus 2006; San Diego-McGlone et al. 2008).

Another problem is toxic algae bloom. The large amounts of nutrients in the case of high pen and stock density result in exponential algae growth, followed by an exhaustion of nutrients and a mass of decaying algae. The latter depletes the water's oxygen by blocking the sun, which suffocates the fish, and its toxicity pollutes the water and poisons them. This has had a negative impact on farm fishing productivity in both Chile and the Philippines.

[2] Lack of effective vaccine against the SRS bacteria in coastal waters affecting salmon has led Chile to use more antibiotics than Norway, Scotland and British Columbia combined, as well as a use of pesticides that is a high multiple of that of British Columbia (Bridsen 2014).

An algae bloom in Chile led to a 16 percent decline in the 2015 salmon output (Bajak 2016) and in a 20 percent downward revision of the 2016 salmon and trout production forecasts (Guardian, March 6, 2016; Financial Times, May 5, 2016), and the problem was still affecting the industry in 2018 (www.undercurrentnews.com, Feb. 7, 2018). Algae bloom has also affected fisheries in Laguna de Bay, the Philippines' largest lake. An Asian Development Bank (ADB 1989) report examined the situation in Laguna de Bay in order to assess the impact of its support of the development of milkfish pens and tilapia cages and found that tilapia and milkfish output had been badly affected by it.[3]

1.1. <u>Congestion</u>

This study is, to my knowledge, the first one to introduce a taxonomy consisting of three economically-relevant congestion categories, namely *low* (LC), *high* (HC) and *super* (SC) congestion. The study contributes to the literature by providing, under these three congestion categories and for both autarky and trade, a general-equilibrium analysis of the steady-state levels of NR, welfare, fishing intensity (or employment) and output in the case of open access to a NR relative to an optimally regulated one, and examining how results are affected by changes in the value of parameters of the preference and production functions and in their functional form. The analysis conducted here is directly applicable to other common-property resource cases (see Section 5).

The three congestion categories are defined here and are explained in more detail in Section 2. First, LC (HC and SC) prevails on the upward-sloping (backward-bending) segment of the average cost or AC curve, and equivalently, on the positive (negative) segment of the marginal cost or MC curve. Second, HC (SC) prevails on the lower (upper) part of the backward-bending segment of the AC curve, with the two separated by the AC curve's inflection point, which – as shown in Figure 1 – is also where the (backward-bending part of the) AC curve and the (positive part of the) MC curve intersect.

The distinction between HC and SC is important as open-access output Q is greater (smaller) than optimal output Q^* – i.e., $Q > (<)\ Q^*$ – under HC (SC). The distinction between SC and HC is also important because of the opposite implications regarding the

[3] A similar problem could also occur in the case of farm/land fish ponds (e.g., see Stephens 1998).

impact of trade policy. Moreover, SC holds over a significantly larger range of output and variable input (or employment) values than HC (see Section 2).

As the welfare cost of open access to a *NR* is greater under HC than LC and is most severe under SC, one would have expected great interest in the HC and SC cases. Nevertheless, an exhaustive online search suggests the issue has not played an important role in the aquaculture literature where production studies have tended to focus on technical efficiency (e.g., Dey et al. 2000; Iliyasu et al. 2016). The backward-bending supply curve for wild fishing has been examined in a few partial-equilibrium studies, though some confusion persists regarding the analysis.[4]

An issue that has become of increasing concern in recent years and is also examined here is the impact of trade on the environment. A common argument is that international trade has led to an increase in environmental degradation in countries with imperfect property rights.[5] Studies dealing with this issue in the case of trade in *NR*-based products – e.g., Chichilnisky (1994) and Copeland and Taylor (1994) – have typically examined it under LC conditions. In this paper, I show that, while this result holds not only under LC but also under HC, the opposite holds under SC.

The remainder of the paper is organized as follows. Section 2 sets forth a two-sector general equilibrium model and preference function, and solves the model under unregulated (open-access) and regulated *NR*. Section 3 considers the autarky case and examines the implications of open access for steady-state welfare, *NR*, variable inputs and output, solves for the optimal tax, and examines the robustness of the results. Free trade is examined in Section 4. Sections 3 and 4 provide both a graphical and algebraic analysis, as well as a set

[4] Copes' (1970) seminal article provides a graphical analysis of the issue for a closed economy in a partial-equilibrium setting. Clark (1990) refers to a discounted supply curve that might be backward bending in the case of an optimally managed fishery (see also Thuy and Flaaten (2013) who refer to these results). This is not possible as variable inputs' marginal product at the optimum must be positive, i.e., the optimum must be on the upward-sloping segment of the AC curve. Gautam et al. (1996) find a backward-bending supply curve in wild fishing caused by a labor-leisure tradeoff rather than negative externalities.

[5] Based on their empirical analysis of sulfur dioxide concentrations from cities across the globe, Copeland and Taylor (2006) find that trade is good for the environment in the *average* country. An early survey of the literature is Dean (1992).

of simulations. Section 5 examines applications of the analysis to other phenomena. Section 6 draws policy implications and Section 7 concludes.

2. Model

Section 2.1 presents the general equilibrium model's supply side, including the production and cost functions, while Section 2.2 provides its demand side. The open-access and optimal solutions are presented in Section 2.3.

2.1. Supply

Assume an economy whose private sector produces two goods under perfect competition, a manufacturing good M and a commodity Q. The economy's endowment of labor is denoted by $\mathbb{L}$, and the amount employed in sector Q (M) is denoted by $L(l)$, with $L + l = \mathbb{L}$. Following Brander and Taylor (1998), I assume the manufacturing good M is produced with l under a constant-returns-to-scale technology. Thus, the marginal product in M, MP_l, is constant. Units are chosen such that $MP_l = 1$, i.e., $M = l = \mathbb{L} - L$. Good M is chosen as the numéraire, with its price normalized to one. Thus, the price of the variable factor is $w = VMP_L = 1$.

In the case of *wild* fishing, the natural resource (*NR*) or fish stock declines with fishing intensity, i.e., with the amount of variable inputs used. In the case of farm fishing (whether in coastal waters, lakes, rivers or pools), *NR* quantity – i.e., the area and amount of water available – is given, though its quality and productive impact is not.

Assume for simplicity that operating a fish pen requires a fixed amount of labor, which is set equal to one. Fish farms may operate a single or multiple fish pens and *NR* quality declines with the number of pens or amount of labor, L, per unit of area, or with their density. The production function is $Q = LN(L), N' < 0, N'' \leq 0$, where N is *NR* quality (as well as Q/L, i.e., labor's average product, AP_L). Marginal product $MP_L = N + LN' \gtreqless 0$. Since $w = 1, AC = 1/AP_L$ and $MC = 1/MP_L$. An open-access equilibrium where $MC >$ $(<)$ 0 is located on the upward-sloping (backward-bending) part of the AC curve where low (high or super) congestion – i.e., LC (HC or SC) – prevails (see Figure 1).

It is surprising that the backward-bending segment of the supply (AC) curve has not been a central part of analyses of open access to common-property resources. Given that it is the locus of the largest negative externalities and the greatest welfare cost, one would have expected it to be of major interest to policy analysts and policymakers. Writing about the backward-bending supply in the case of road travel, Thomps (1998) states: "… [it] is usually referred to … as "unstable" and ignored as irrelevant ..."

Assume $N = \alpha - \beta L$ $(\alpha, \beta > 0)$, where α is the *NR* endowment or *NR* quality in the absence of farm fishing. Then, production functions for Q and M are given by:

$$Q = LN = L(\alpha - \beta L), M = l = \mathbb{L} - L; \;\; \alpha, \beta > 0, L \,\epsilon \left(0, \frac{\alpha}{\beta}\right) \qquad (1)$$

where β reflects the negative externality, and $L < \alpha/\beta \Leftrightarrow N = \alpha - \beta L > 0$.

Thus, labor's average product $AP_L = \frac{Q}{L} = N = \alpha - \beta L > 0$. With $w = 1$, average cost $AC = \frac{1}{AP_L} = \frac{1}{\alpha - \beta L}$.[6] Labor's marginal product $MP_L = \alpha - 2\beta L$, and marginal cost $MC = \frac{1}{MP_L} = \frac{1}{\alpha - 2\beta L}$. Denote maximum output – or NR's 'carrying capacity' – by $\hat{Q}$ (Q_{MAX} in Figure 1), with $\hat{Q} = \frac{\alpha^2}{4\beta}$, produced with $\hat{L} = \frac{\alpha}{2\beta}$ where $MP_L = 0$. Also, MP_L and $MC = \frac{1}{MP_L}$ $\gtrless 0$ for $L \lesseqgtr \hat{L}$, with $\lim_{L^- \to \hat{L}} MC \left(\lim_{L^+ \to \hat{L}} MC\right) = \infty \; (-\infty)$. In other words, and as shown in Figure 1, MC jumps from ∞ to $-\infty$ as L crosses $\hat{L}$ from $L < \hat{L}$ to $L > \hat{L}$ and MP_L changes from infinitesimally positive to zero to infinitesimally negative.

Output Q is quadratic in L, i.e., it has two solutions, L_1 and L_2, with $Q = L_1 N_1 = L_2 N_2$. The solution is $L_1 = \frac{\alpha}{\beta} - L_2$ or $L_1 + L_2 = \frac{\alpha}{\beta}$,[7] with two possible outcomes: i) $L_1 = L_2 =$

[6] Labor is not the only costly input. Other ones are pens, fish fry and feed. One can reasonably assume that these are directly related to the amount of labor used, i.e., the per-unit cost would be $1 + \gamma$, where γ is the cost of pens and fish fry relative to the unitary wage rate, an element that can easily be incorporated in the analysis. For simplicity, and following Brander and Taylor (1998), I abstract from non-labor costs.

[7] With $Q = L_1 N_1 = L_2 N_2$, or $Q = L_1(\alpha - \beta L_1) = L_2(\alpha - \beta L_2)$, we have $\beta L_1^2 - \alpha L_1 + L_2(\alpha - \beta L_2) = 0$, with $L_1 = \frac{\alpha \pm \sqrt{\alpha^2 - 4\beta L_2(\alpha - \beta L_2)}}{2\beta} = \frac{\alpha \pm \sqrt{(\alpha - 2\beta L_2)^2}}{2\beta} = \frac{\alpha \pm (\alpha - 2\beta L_2)}{2\beta}$. We have two solutions, one for $L_1 \neq L_2$ and one for $L_1 = L_2$, namely: i) $L_1 \neq L_2$: $L_1 = \frac{\alpha + (\alpha - 2\beta L_2)}{2\beta} = \frac{\alpha}{\beta} - L_2$, or $L_1 + L_2 = \frac{\alpha}{\beta}$; and ii) $L_1 = \frac{\alpha - (\alpha - 2\beta L_2)}{2\beta} = L_2 = \frac{\alpha}{2\beta} = \hat{L}$, with i) $N_1 = \alpha - \beta L_1 = \beta L_2$, $N_2 = \beta L_1$, $N_1 + N_2 = \alpha$, $N_1 < \frac{\alpha}{2} < N_2$; and ii) $N_1 = N_2 = \frac{\alpha}{2}$, i.e., the *NR* level is equal to half the initial endowment, α.

$\hat{L} = \frac{\alpha}{2\beta}$, $N = \hat{N} = \alpha - \beta\hat{L} = \frac{\alpha}{2}$, $Q = \hat{Q}$, or ii) $Q < \hat{Q}$, with output produced either with a low $L_2 < \hat{L}$ and high $N_2 > \frac{\alpha}{2}$ (in LC's case) or with a high $L_1 > \hat{L}$ and low $N_1 < \frac{\alpha}{2}$ (HC or SC case), with the former (latter two) located on the upward-sloping (backward-bending) segment of the AC curve. This is depicted by points A (LC) and A' (SC) in Figure 1.

The distinction between the HC and SC categories is important because of their implications for the welfare cost of open access. SC (HC) is defined as the segment of the backward-bending AC curve where optimal output, Q^*, is greater (smaller) than open-access output, Q. The fact that $Q < Q^*$ under SC, i.e., that open-access output is smaller than optimal output, is one of the reasons why the welfare cost of open access is so high under SC, the other reason being the higher cost. And as we shall see, a number of opposite results obtain under the HC and SC congestion categories.

I derive now the critical level of L, L_I, that separates the HC and SC categories. Denote variables under open access (optimal regulation) by subscript 1 (2). The point that separates SC from HC is where optimal output is equal to open-access output, i.e., where the AC curve intersects the (positive segment of the) MC curve. Thus, L_I is the level of L where $Q_1 = Q_2$, which occurs where $AC_1 = MC_2$, i.e., where $\frac{1}{\alpha - \beta L_1} = \frac{1}{\alpha - 2\beta L_2}$ or $L_1 = 2L_2$. Since $L_1 = \frac{\alpha}{\beta} - L_2$ (see footnote 8), we have $L_1 = \frac{2\alpha}{3\beta}$ and $L_2 = \frac{\alpha}{3\beta}$. As L_I separates HC and SC, it is located on the backward-bending segment of the AC curve, i.e., $L_I = L_1 = \frac{2\alpha}{3\beta}$. Output Q_I can be produced with $L_I = 2\alpha/3\beta$ (and $N_1 = \alpha - \beta L_1 = \alpha/3$) or with $L_2 = \frac{L_I}{2} = \alpha/3\beta$ (and $N_2 = 2\alpha/3$), i.e., it can be produced at the optimum at half the cost prevailing under open access, in terms of *both* variable inputs L and natural resource N.

Based on the solution for $L = \hat{L}$ and $L = L_I$, the three congestion categories' definition is:

Definition 1. LC: $0 < L < \hat{L} = \frac{\alpha}{2\beta}$; HC: $\hat{L} < L < L_I = \frac{2\alpha}{3\beta}$; and SC: $L_I < L < \frac{\alpha}{\beta}$.

The definition of these categories in terms of output $Q = L(\alpha - \beta L)$ is:

Definition 2. LC: $0 < Q < \hat{Q} = \frac{\alpha^2}{4\beta}$; HC: $Q_I = \frac{2\alpha^2}{9\beta} < Q < \hat{Q}$; and SC: $0 < Q < Q_I$.

Thus, the range of variable input values, L, is $\frac{\alpha}{6\beta}$ under HC, $\frac{\alpha}{3\beta}$ under SC and $\frac{\alpha}{2\beta}$ under LC. The range of output values, Q, is $\frac{\alpha^2}{36\beta}$ under HC, $\frac{2\alpha^2}{9\beta}$ under SC and $\frac{\alpha^2}{4\beta}$ under LC. Thus, in terms of L (Q), the range of values under SC is *twice* (*eight* times) that under HC.[8] And the range of values of $L(Q)$ under LC is *three* (*nine*) times that under HC.

Note that L_{I}, which separates HC from SC, is also the inflection point on the backward-bending segment of the AC curve. As L increases and Q declines, AC increases at an increasing (decreasing) rate under SC (HC), with $\frac{\partial^2 AC}{\partial Q^2} < (>)\ 0$. Thus, L_I can also be obtained by solving $\frac{\partial^2 AC}{\partial Q^2} = 0$.[9]

Finally, $MC_1 < 0$ is the mirror image of $MC_2 > 0$.[10] This is depicted in Figure 1.

2.2. Demand

Individual preferences are represented by a Cobb-Douglas utility function:

$$U = m^{1/2}q^{1/2}, \tag{2}$$

where $m = M/\mathbb{L}$ and $q = Q/\mathbb{L}$.

[8] In term of L, the range of values under HC is $\frac{2\alpha}{3\beta} - \frac{\alpha}{2\beta} = \frac{\alpha}{6\beta}$, while the range of values under SC is $\frac{\alpha}{\beta} - \frac{2\alpha}{3\beta} = \frac{\alpha}{3\beta}$, or twice the range under HC. In terms of Q, $\hat{Q} = \frac{\alpha^2}{4\beta}$ and $Q_I = \frac{2\alpha^2}{9\beta} = \frac{8}{9}\hat{Q}$. Thus, the range of values under HC is $\hat{Q} - Q_I = \frac{1}{9}\hat{Q}$. Under SC, the range of values is between $Q_I = \frac{8}{9}\hat{Q}$ and zero (for $L = \frac{\alpha}{\beta}$) or $\frac{8}{9}\hat{Q}$. Thus, the range of output values under SC is 8 times the range of values under HC.

[9] Denoting $\frac{\partial AC}{\partial Q}$ by AC' and $\frac{\partial^2 AC}{\partial Q^2}$ by AC'', $AC' = \frac{\partial AC}{\partial L} \cdot \frac{\partial L}{\partial Q} = \frac{\partial AC}{\partial L} / \frac{\partial Q}{\partial L} = \frac{\beta}{(\alpha-\beta L)^2(\alpha-2\beta L)} \gtreqless 0 \Leftrightarrow \alpha - 2\beta L \gtreqless 0 \Leftrightarrow L \lesseqgtr \hat{L} = \frac{\alpha}{2\beta}$. As shown in Figure 1, the slope of the AC curve is positive (negative) in its LC (HC and SC) segment. The change in the slope is $AC'' = \frac{\partial AC'}{\partial L} / \frac{\partial Q}{\partial L} = \frac{2\beta^2(2\alpha-3\beta L)}{(\alpha-\beta L)^3(\alpha-2\beta L)^3}$. Thus, $AC'' = 0$ at $L = L_I = \frac{2\alpha}{3\beta}$. Also, as Q increases: i) $AC'' > 0$ under LC ($L < \hat{L}$), ii) $AC'' < 0$ under HC ($\hat{L} < L < L_I$) and iii) $AC'' > 0$ under SC ($L_I < L < \alpha/\beta$).

[10] MC under optimal regulation is $MC_2 = \frac{1}{\alpha-2\beta L_2} > 0$, $L_2 < \hat{L}$. Thus, $-MC_2 = \frac{1}{2\beta L_2-\alpha} < 0$. MC under open access is $MC_1 = \frac{1}{\alpha-2\beta L_1} < 0$, $L_1 > \hat{L}$. At the same output, $L_2 = \frac{\alpha}{\beta} - L_1$ (see fn. no. 8). Thus, $2\beta L_2 - \alpha = 2\beta\left(\frac{\alpha}{\beta} - L_1\right) - \alpha = \alpha - 2\beta L_1$, i.e., $MC_1 = -MC_2$. In other words, MC_1 is the mirror image of MC_2.

3. Autarky

Section 3.1 presents a graphical analysis, Section 3.2 provides the solution to the model, and Section 3.3 presents various simulations. Welfare in Section 3.1 is aggregate welfare $W = \mathbb{L}U$, while welfare in Sections 3.2 and 3.3 is the representative individual's utility U, a distinction that matters when examining the impact of changes in $\mathbb{L}$.

3.1. Graphical analysis

Assume first that a country's demand for Q is represented by line D in Figure 1. Open-access equilibrium is at point A – which is located in the LC segment of the AC curve – and output is Q_0. The optimum is at point E where output is Q_1. The welfare cost under open access is $\Delta W_{LC} = W_{LC}^* - W_{LC} = AEB$.

Assume now a country whose demand is represented by line D' because, say, of a larger population (or greater preference for Q). Open-access equilibrium is at point A' where AC and D' intersect and which is located in the SC segment of the AC curve. For simplicity, assume D' is such that output is also Q_0 at A'. The optimum is at E' where D' and MC intersect. [11]

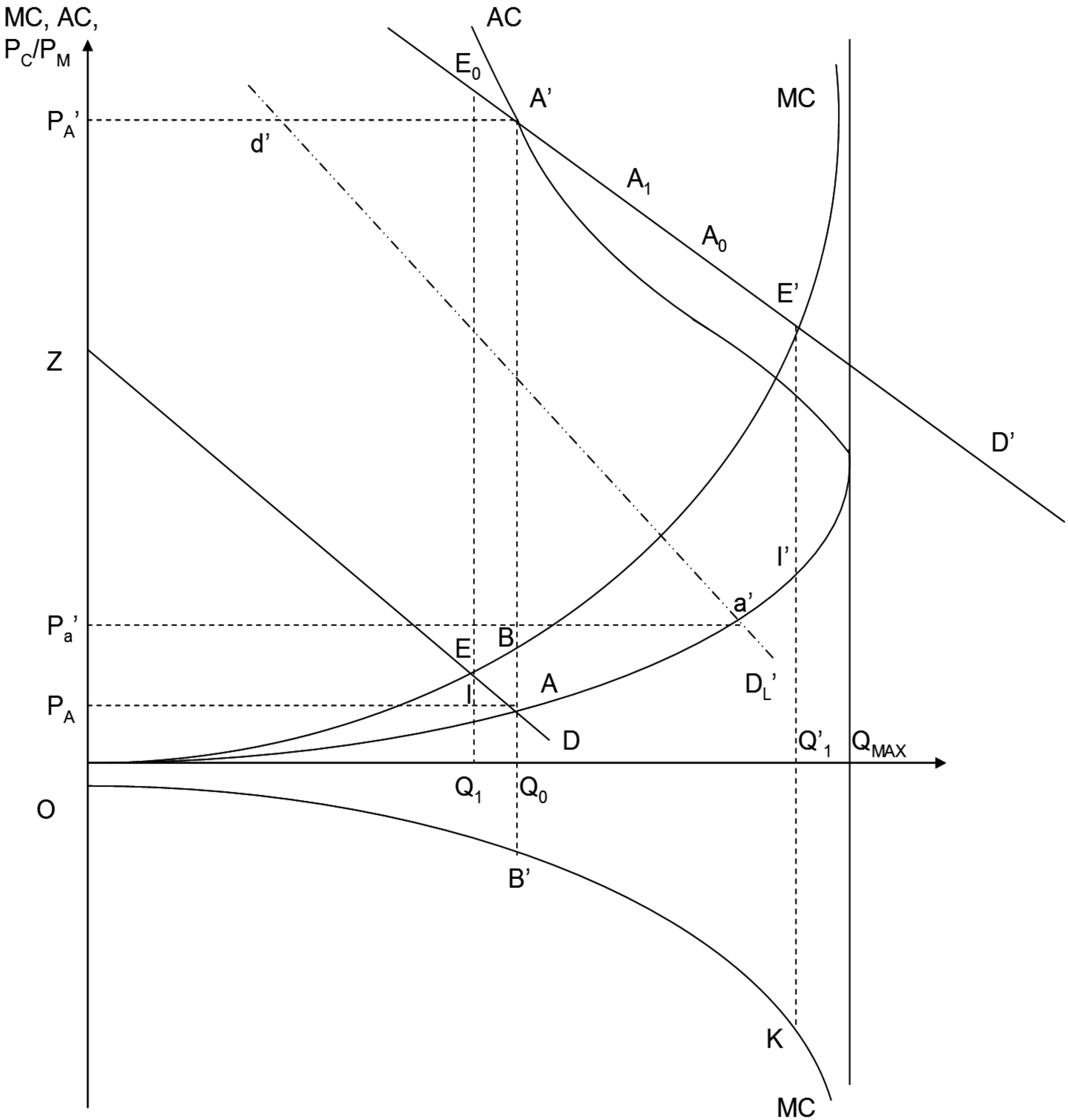
There are three ways to obtain the welfare cost, ΔW_{SC}, of open access in this case:

1. The difference in the cost of producing Q_0 under demand D and D' is $P_A'A'AP_A =$ (Distance AA')$*\, Q_0$, while the increase in output from Q_0 to Q_1' generates the gain $A'E'B$. Hence, the welfare cost of open access is $\Delta W_{SC} = P_A'A'AP_A + A'E'B$.

2. Note that there is no producer surplus under open access as $p = AC$. Hence, welfare is equal to the consumer surplus, i.e., the area between the demand curve and the price line. At A', the consumer surplus is the area below the demand curve and above the $P_A'A'$ line. At E', AC is given by point I', so that welfare is the area between the demand curve and the horizontal line at the I' level (or the line $P_I'I'$, with point P_I' on the y-axis not shown). Thus, the welfare cost is equal to the area between the lines $P_A'A'$, $P_I'I'$ (the horizontal line through point I') and the demand curve, i.e., $\Delta W_{SC} = P_A'A'E'I'P_I'$.

[11] The HC segment is the area between AC's turning point where $Q = Q_{MAX}$ (or $\hat{Q}$ in Section 2.1) and the point where MC and AC intersect.

Figure 1: Autarky under Low and High Congestion



3. Consumption is Q_0 rather than $Q_1' > Q_0$, with a loss equal to $A'Q_0Q_1'E'$. Second, the *decrease* in output from Q_1' to Q_0 implies a *higher* production cost. The cost increase has three components: i) the cost of the increase in output from Q_1' to Q_{MAX}, which is equal to the area below the MC curve, i.e., $E'Q_1'Q_{MAX}\infty$; ii) the cost of the decrease in output from Q_{MAX} to Q_1' on the backward-bending part of the AC curve, equal to $KQ_1'Q_{MAX}$(-∞); and iii) the cost of the decrease in output from Q_1' to Q_0, i.e., the area $B'Q_0Q_1'K$. Thus, the welfare cost, ΔW_{SC}, of open access in this case is $\Delta W_{SC} = A'B'KE' + E'\infty(-\infty)K$.[12]

The reasons for the difference between welfare cost under HC, ΔW_{HC}, and under SC, ΔW_{SC}, are: optimal output is larger (smaller) than open-access output for SC (HC) – with a welfare gain $A'B'KE'$ under SC [13] – and the decline in cost is greater under SC.

The analysis suggests that ΔW_{HC} and especially ΔW_{SC} is significantly larger than ΔW_{LC}. The difference between them is dampened when it comes to the representative individual's utility $U = W/\mathbb{L}$ rather than to aggregate welfare W if demand D' is larger than D due to a larger population $\mathbb{L}$ and not a difference in taste. Nevertheless, the utility cost under HC and SC is either a multiple or a greater order of magnitude than under LC (see Section 3.3).

As $p = AC$ under open access, the producer surplus is nil and the *NR* value is zero. However, though its private value is nil, the *NR*'s social value is positive as it generates a consumer surplus under a positive output that is partly consumed domestically.

3.1.1. Migration

Assume a developed country allows a given number of individuals to immigrate. This results in a decrease in demand, from D' to D_L' in Figure 1, and raises welfare, with the

[12] Given that the negative segment of the MC curve is the mirror image of its positive segment, the welfare cost is also $\Delta W_{SC} = A'B'KE' + 2 * E'Q_1'Q_{MAX}\infty$.

[13] Assume HC prevails, with the demand curve – denoted by D_2 (not shown in Figure 1) – intersecting the backward-bending segment of the AC curve at an output Q_2 (not shown), with $Q_I < Q_2 < Q_{MAX}$, where $Q_I = L_I(\alpha - \beta L_I)$ corresponds to the output where AC and MC intersect ($L_I = \frac{2\alpha}{3\beta}$, $Q_I = \frac{2\alpha^2}{9\beta}$). As is clear from Figure 1, optimal output, Q_2^*, the output where D_2 and MC intersect, is smaller than Q_I. Thus, $Q_2^* < Q_I < Q_2$, and $p_2^* > p_I > p_2$. Thus, contrary to SC, HC's optimal output (price) is smaller (higher) than open-access output.

increase largest if SC prevails initially and LC prevails after migration, in which case welfare rises from the area above $P_A'd'$ and below D_L', to the area $P_A'd'a'P_a'$.

3.2. Solution

This section provides the solution to the model for both an unregulated (open-access) and an optimally regulated *NR*.

3.2.1. Open Access

Utility maximization implies that the commodity's relative price, p, equals the ratio of marginal utilities, i.e., $p = \frac{U_q}{U_m} = \frac{m}{q} = \frac{M}{Q} = \frac{\mathbb{L}-L}{L(\alpha-\beta L)}$, where $AP_L = \alpha - \beta L > 0$ or $L < \frac{\alpha}{\beta}$. Under open access, $p = AC = \frac{1}{\alpha-\beta L}$. Thus, $\frac{\mathbb{L}-L}{L(\alpha-\beta L)} = \frac{1}{\alpha-\beta L}$ or $L = \frac{\mathbb{L}}{2}$. Consequently, the condition $L < \frac{\alpha}{\beta}$ is equivalent to $\mathbb{L} < \frac{2\alpha}{\beta}$. The solution is:

$$L = \frac{\mathbb{L}}{2}, M = \frac{\mathbb{L}}{2}, m = \frac{1}{2}, Q = \frac{\mathbb{L}}{2}\left(\alpha - \frac{\beta\mathbb{L}}{2}\right), q = \frac{1}{2}\left(\alpha - \frac{\beta\mathbb{L}}{2}\right), U = \frac{1}{2}\left(\alpha - \frac{\beta\mathbb{L}}{2}\right)^{1/2}. \qquad (3)$$

3.2.2. Optimum

Under optimal regulation, $p = MC$, or $\frac{M}{Q} = \frac{\mathbb{L}-L}{L(\alpha-\beta L)} = \frac{1}{\alpha-2\beta L}$, which is a quadratic equation, namely $3\beta L^2 - 2(\alpha + \beta\mathbb{L})L + \alpha\mathbb{L} = 0$. The solution is:

$$L^* = \frac{1}{3\beta}\left(\alpha + \beta\mathbb{L} - \sqrt{\alpha^2 + \beta^2\mathbb{L}^2 - \alpha\beta\mathbb{L}}\right), M^* = \mathbb{L} - L^*, \qquad (4)$$

[14]

with the representative individual's output $q^* = L^*(\alpha - \beta L^*)/\mathbb{L}$ and $m^* = 1 - L^*/\mathbb{L}$.

Note that equations (3) and (4) imply $L^* < L$. [15] [16]

[14] The sign in front of the square root is negative as $\sqrt{\alpha^2 + \beta^2\mathbb{L}^2 - \alpha\beta\mathbb{L}} = \sqrt{(\alpha - \beta\mathbb{L})^2 + \alpha\beta\mathbb{L}} > \alpha - \beta\mathbb{L}$, i.e., a positive sign implies $L^* > 2\alpha/3\beta$, which cannot be as L^* must be located in the LC segment of the AC curve where $MP_L > 0$, i.e., $L^* < \hat{L} = \alpha/2\beta$.

[15] Assume the opposite, i.e., $L = \frac{\mathbb{L}}{2} \leq L^* = \frac{1}{3\beta}\left[\alpha + \beta\mathbb{L} - \sqrt{\alpha^2 + \beta^2\mathbb{L}^2 - \alpha\beta\mathbb{L}}\right]$, or $\frac{3\beta\mathbb{L}}{2} \leq \alpha + \beta\mathbb{L} - \sqrt{\alpha^2 + \beta^2\mathbb{L}^2 - \alpha\beta\mathbb{L}}$, i.e., $\sqrt{\alpha^2 + \beta^2\mathbb{L}^2 - \alpha\beta\mathbb{L}} \leq \alpha - \frac{\beta\mathbb{L}}{2} = AP_L$. With $AP_L > 0$, we have $\alpha^2 + \beta^2\mathbb{L}^2 - \alpha\beta\mathbb{L} \leq \alpha^2 + \frac{\beta^2\mathbb{L}^2}{4} - \alpha\beta\mathbb{L}$, or $\beta^2\mathbb{L}^2 \leq \frac{\beta^2\mathbb{L}^2}{4}$, which is false. Thus, $L^* < L$.

[16] From (1), (2), and (4), $U^* = \frac{1}{3\beta\mathbb{L}}\left[\alpha\beta\mathbb{L}(\alpha + \beta\mathbb{L}) - \frac{2}{3}(\alpha^3 + \beta^3\mathbb{L}^3) + \frac{2}{3}(\alpha^2 + \beta^2\mathbb{L}^2 - \alpha\beta\mathbb{L})^{3/2}\right]^{1/2}$.

3.3. Simulation

Define $\nabla x \equiv (x - x^*)/x^*$, $x = U, N, Q, L$. This section examines the relationship between ∇x and parameter $\mathbb{L}$, for given values of *NR* endowment, α, and externality parameter, β. Robustness of the results is examined in Section 3.4 by using i) different values for the production and utility function parameters, and ii) different functional forms.

The 'base case' values for α and β are $\alpha = 10$ and $\beta = 1$ (other cases are examined in Section 3.4). Table 1 shows results for individual $\mathbb{L}$-values and Table 2 does the same for central values of $\mathbb{L}$ in each of the three congestion categories.

A. Results for individual $\mathbb{L}$ values

i) Welfare

Table 1 shows $\nabla U_1 = -.033$ (for $\mathbb{L} = 1$), $\nabla U_4 = -.707$, $\nabla U_9 = -6{,}07$, $\nabla U_{11} = -13.5$, $\nabla U_{16} = -33.3$, and $\nabla U_{19} = -64.3$ percent, with LC (HC) (SC) for the first three (fourth) (last two) $\mathbb{L}$ values. Thus, $\nabla U_{19} = 1983\nabla U_1$, $91\nabla U_4$ and $10.6\nabla U_9$ (LC cases) and $\nabla U_{19} = 4.8\nabla U_{11}$ (the HC case). Thus, the welfare cost of open access for $\mathbb{L} = 19$ is from one to three degrees of magnitude greater than under LC and is a multiple of that under HC.

- For $\mathbb{L} = 16$ (which is below $\mathbb{L}$'s central value of 16.67 under SC), $\nabla U_{16} = 1028\nabla U_1$, $47.12\nabla U_4$ and $5.62\nabla U_9$, and $2.47\nabla U_{11}$. Thus, ∇U_{16} is between three degrees of magnitude greater and a multiple of welfare costs under LC and is a multiple of ∇U_{11} under HC.

- For $\mathbb{L} = 11$ (which is below $\mathbb{L}$'s central value of 11.67 under HC), $\nabla U_{11} = 148\nabla U_1$, $19.1\nabla U_4$ and $2.28\nabla U_9$. In other words, ∇U_{11} is between two degrees of magnitude greater and a multiple of welfare costs under LC.

ii) Natural Resource

- For $\mathbb{L} = 19$ (an SC case), ∇N_{19} is -91 percent or $827\nabla N_1$, $31.4\nabla N_4$, and $3.7\nabla N_9$ for the LC cases, and $2.93\nabla N_{11}$ for the HC case. For $\mathbb{L} = 16$ (an SC case), $\nabla N_{16} = -67$ percent or $608\nabla N_1$, $23.1\nabla N_4$ and $2.68\nabla N_9$ for the LC cases, and $2.16\nabla N_{11}$ for the HC case.

- Thus, ∇N_{19} and ∇N_{16} are both between two orders of magnitude greater and a multiple of ∇N under LC and a multiple of ∇N under HC.

- The same result obtains for HC relative to LC, with $\nabla N_{11} = -31$ percent or $282\nabla N_1$, $10.7\nabla N_4$ and $1.35\nabla N_9$.

Table 1. Autarky: Open Access vs. Optimum

$\mathbb{L}$	Open Access (x)				Optimum (x^*)				Difference $\nabla x = \frac{x-x^*}{x^*}$ (%)			
	L	N	Q	U	L^*	N^*	Q^*	U^*	∇L	∇N	∇Q	∇U
1	.50	9.5	4.75	1.541	.49	9.51	4.63	1.542	2.7	-.11	1.06	-.033
4	2.0	8.0	16.0	1.414	1.8	8.2	14.5	1.424	15	-2.9	10.3	-.707
9	4.5	5.5	24.8	1.173	3.2	6.8	21.6	1.248	43	-25	14.6	-6.07
11	5.5	4.5	24.8	1.061	3.5	6.5	22.8	1.226	58	-31	9.0	-13.5
16	8.0	2.0	16.0	.7071	4.0	6.0	24.0	1.061	100	-67	-33	-33.3
19	9.5	.50	4.75	.3536	4.2	5.8	24.4	.991	127	-91	-81	-64.3

iii) Employment

$\nabla L_{19} = 127$ percent, or $47\nabla L_1$, $8.5\nabla L_4$ and $3.0\nabla L_9$ (LC cases), and 2.2 ∇L_{11} (HC case).
- Thus, for the SC case, the excess employment (variable input use) is between one order of magnitude larger and a multiple of that under LC, and a multiple of that under HC.

iv) Output

$\nabla Q < (>)\ 0$ under LC and HC (SC), i.e., optimal output is smaller (larger) for LC and HC (SC) than open-access output. As a small tax, τ, raises cost and reduces L, the output effect $\partial Q/\partial\tau < (>) 0$ under LC (HC and SC), i.e., ∇Q and $\partial Q/\partial\tau$ have opposite signs for HC.

Table 2. Open Access vs. Optimum under Autarky: Central $\mathbb{L}$ Values [a]

$\mathbb{L}$	Open Access (x)		Optimum (x^*)		Difference (%) $\nabla x = \frac{x-x^*}{x^*}$		Ratio ($\nabla x/\nabla x_{LC}$)	
	N	U	N^*	U^*	∇N	∇U	$\nabla N/\nabla N_{LC}$	$\nabla U/\nabla U_{LC}$
LC: 5.0	7.5	1.369	7.9	1.387	-4.9	-1.29	1	1
HC: 11.67	4.2	1.021	6.4	1.169	-35	-12.7	7.1	9.8
SC: 16.67	1.7	.6455	5.9	1.046	-72	-38.3	14.7	29.7

a: Results are for the central values of $\mathbb{L}$ in each one of the three congestion categories.

B. Results for central $\mathbb{L}$ values

Table 2 presents the welfare and *NR* results associated with the central value of $\mathbb{L}$ in each the three congestion categories, namely $\mathbb{L} = 5.0\ (11.67)\ (16.67)$ for LC (HC) (SC).

The welfare cost $\nabla U_{SC} = -38.3$ percent, or $29.7\nabla U_{LC}$ and $3.0\nabla U_{HC}$, and $\nabla U_{HC} = 9.8\nabla U_{LC}$. The *NR* cost $\nabla N_{SC} = -72$ percent, or $14.7\nabla N_{LC}$ and $2.1\nabla N_{HC}$, and $\nabla N_{HC} = 7.1\nabla N_{LC}$.

Thus, even though analyses have focused on the low-congestion (LC) category, Table 2 shows that the central result for open access' welfare impact under SC (HC) is of a greater order of magnitude (a multiple) of that under LC, with a welfare cost of about 30 (10) times that of the latter. Moreover, the *NR* impact under SC (HC) is also of a greater order of magnitude (a multiple) of that under LC, with a *NR* loss of about 15 (7) times that under LC. These results suggest that studies have for the most part focused on the least important congestion category.

3.3.1. Production tax

Appendix 1 provides the optimal tax solution and a table (Table 1A) with optimal tax rates. Denote the tax rate by τ, with $p = (1 + \tau)p_\tau$, where p_τ is the producer price. The optimal tax rate, τ^*, as a function of $\mathbb{L}$, is provided for two sets of parameter values, namely α (β) = 10 (1) and α (β) = 10 (2). In the case of $\alpha = 10$ and $\beta = 1$, τ^* is (in percent) 255 for $\mathbb{L} = 19$, 200 for $\mathbb{L} = 16$, 85.4 for $\mathbb{L} = 9$, 27.2 for $\mathbb{L} = 4$, and 5.4 for $\mathbb{L} = 1$. Thus, the optimal tax rate under SC, i.e., for $\mathbb{L} = 19$ $(16)(9)$ is 47.2 (37.0) (15.8) times that for $\mathbb{L} = 1$ and is 15.8 times the $\mathbb{L} = 1$ rate in the case of $\mathbb{L} = 9$ under HC.

The optimal tax increases with the externality parameter, β, and decreases with the endowment parameter, α. For instance, the level of τ^* for $\beta = 2$ is double to triple the corresponding level for $\beta = 1$. In the case of $\alpha = 10$, $\tau^* = 621$ for $\mathbb{L} = 19$ (2.4 times the $\beta = 1$ rate), 504 for $\mathbb{L} = 16$ (2.5 times the $\beta = 1$ rate), 236 for $\mathbb{L} = 9$ (2.8 times the $\beta = 1$ rate), and 11.7 for $\mathbb{L} = 1$ (2.2 times the $\beta = 1$ rate).

The increase in the optimal tax rate as $\mathbb{L}$ increases helps dampen the increased pressure on the *NR*. This can be seen from Table 1 where the decline in *NR* and welfare as $\mathbb{L}$ increases from 1 to 19 under the optimal tax is half that under open access.

Under SC, a tax $\tau < \tau^*$ results in an equilibrium at points like points A_0 or A_1 in Figure 1.

3.4. Robustness

This section examines the robustness of the relationship between congestion levels and ∇x by using *a*) different values for the utility and production function parameters, and *b*) different functional forms. Solutions and results are provided in Appendix 2.

3.4.1. Alternative parameter values

The values of ∇U and ∇N do not depend on the value of the individual production function parameters α and β but rather depend on the value of their ratio, α/β. In other words, results for (α, β) also hold for $(\lambda\alpha, \lambda\beta)$, $\lambda > 0$.[17] The analysis so far assumed $\alpha/\beta = 10$. The values of α/β used here are: *i*) 2, *ii*) 6, *iii*) 20, and *iv*) 100. Results for case *i*) (*ii*)) are shown in Panel A (B) of Table 2A, Appendix 2.

Recall that output $Q > 0$ requires that $AP_L = \alpha - \beta\mathbb{L}/2 > 0$ or $\mathbb{L} < 2\alpha/\beta$.

i) $\underline{\alpha/\beta = 2}$

For $\mathbb{L} = 3$ (under SC), ∇U_3 $(\nabla N_3) = -27$ (-59) percent or $17\nabla U_1$ $(12\nabla N_1)$.

ii) $\underline{\alpha/\beta = 6}$

For $\mathbb{L} = 11$ (under SC), ∇U_{11} $(\nabla N_{11}) = -55$ (-86) percent, or $162\nabla U_1$ $(210\nabla N_1)$ and $107\nabla U_2$ $(45\nabla N_2)$ for LC cases, and $8.3\nabla U_6$ $(3.4\nabla N_6)$ under HC.

iii) $\underline{\alpha/\beta = 20}$

∇U_{19} $(\nabla N_{19}) = -7.056$ (-22.3) percent, or $552\nabla U_1$ $(679\nabla N_1)$ and $21.0\nabla U_4$ $(24.8\nabla N_4)$.

iv) $\underline{\alpha/\beta = 100}$

∇U_{19} $(\nabla N_{19}) = -.137$ $(-.544)$ percent, or $427\nabla U_1$ $(431\nabla N_1)$ and $16.2\nabla U_4$ $(16.5\nabla N_4)$.

As for preferences, a general form of the utility function in equation (2) is:

$$U = q^{\gamma} m^{1-\gamma}, \gamma \in (0, 1). \tag{5}$$

[17] As $L^* = \frac{1}{3\beta}\left[\alpha + \beta\mathbb{L} - \sqrt{\alpha^2 + \beta^2\mathbb{L}^2 - \alpha\beta\mathbb{L}}\right] = \frac{1}{3}\left[\frac{\alpha}{\beta} + \mathbb{L} - \sqrt{\left(\frac{\alpha}{\beta}\right)^2 + \mathbb{L}^2 - \left(\frac{\alpha}{\beta}\right)\mathbb{L}}\right]$, it is clear that L^* only depends on the ratio α/β (and $\mathbb{L}$). Hence, the same holds for $M^* = \mathbb{L} - L^*$ and $m^* = M^*/\mathbb{L}$, while $Q^*_\lambda = L^*(\lambda\alpha - \lambda\beta L^*) = \lambda L^*(\alpha - \beta L^*) = \lambda Q^*$ and $q^*_\lambda = \lambda q^*$. Thus, $U^*_\lambda = \lambda^{.5} U^*$. And as $L = \mathbb{L}/2$ is independent of α and β, so is M and m, while $Q_\lambda = \lambda Q$ and $U_\lambda = \lambda^{.5} U$. Thus, $\nabla U_\lambda = (U_\lambda - U^*_\lambda)/U^*_\lambda = \nabla U$. The same holds for ∇N as $N^*_\lambda = \lambda N^*$ and $N_\lambda = \lambda N$, so that $\nabla N_\lambda = \nabla N$.

Equation (2) assumed $\gamma = .5$. As the share of farmed fish in an individual's budget is likely to be significantly below $.5$, ratios $\nabla U_{19}/\nabla U_1$ and $\nabla N_{19}/\nabla N_1$ are examined for $\gamma = .1$ and $\gamma = .2$. For $\gamma = .1$, we have $\nabla U_{19}/\nabla U_1 = 183$ and $\nabla N_{19}/\nabla N_1 = 204$. And for $\gamma = .2$, we have $\nabla U_{19}/\nabla U_1 = 60.1$ and $\nabla N_{19}/\nabla N_1 = 105$.

Thus, the findings that the welfare cost under HC and SC is a multiple or of a greater order of magnitude than under LC also holds for alternative values of the parameters of the production and utility functions.

3.4.2. Alternative functional forms

Two alternative utility functions and two alternative production functions are examined below. The solutions and simulation results are provided in Appendix 3.

A. Utility functions

I. The first (constant-relative-risk-aversion) utility function is $U(x) = \frac{x^{1-\mu}}{1-\mu}$, $\mu \neq 1$. Assuming separability and $\mu = 1/2$, we have:

$$U(m,q) = U(m) + U(q) = \frac{m^{1/2}}{1/2} + \frac{q^{1/2}}{1/2}. \tag{6}$$

The solution is derived from a quadratic equation for (open-access) L and from a cubic equation for (optimal) L^*. Simulation results for $\beta = 1$ are presented in Table A2 in Appendix 3 and are discussed below.

In Panel A, $\alpha = 6$, LC prevails for $\mathbb{L} < 6$. In percent, $\nabla U_1(\nabla N_1) = -.19\ (-.93)$, $\nabla U_3\ (\nabla N_3) = -3.4\ (-14.9)$ or $18\nabla U_1$ $(16.1\nabla N_1)$, $\nabla U_5\ (\nabla N_5) = -9.0\ (-36.4)$ or $47.3\nabla U_1$ $(38.2\nabla N_1)$. Thus, ∇U and ∇L at middle and higher congestion levels *within* the LC category are an order of magnitude greater than at lower ones. SC prevails for $8 < \mathbb{L} < 12$. For $\mathbb{L} = 10$, we have, in percent, $\nabla U_{10}(\nabla N_{10}) = -21.5\ (-71.7) = 113\nabla U_1(77.2\nabla N_1)$. Comparing $\mathbb{L}$'s central values for SC and LC, we have $\nabla U_{10}(\nabla N_{10}) = 20.6\nabla U_3\ (14.6\nabla N_3)$. Similar results obtain for $\alpha = 4$ (as shown in panel B).

Thus, as with the original utility function in (2), the welfare and *NR* losses under SC are a multiple of those under LC or are of a greater order of magnitude.

II. The second utility function is:

$$U = \left(m - \frac{m^2}{2}\right) + \left(q - \frac{q^2}{2}\right), m = \frac{M}{\mathbb{L}}, q = \frac{Q}{\mathbb{L}}. \quad (7)$$

The solution is derived from a cubic equation for both L and L^*. Solution and simulation results are in Appendix 3. For $\alpha = 2$ and $\beta = 1$, ∇U_1 $(\nabla N_1) = -.375$ (-2.90) percent, ∇U_5 $(\nabla N_5) = -7.77(-77.5)$ percent or $20.7\nabla U_1$ $(26.7\nabla N_1)$, and ∇U_{10} $(\nabla N_{10}) = -12.1$ (-81) percent or $32.1\nabla U_1$ $(28\nabla N_1)$.

As with the original utility function in (2) and the one in (6), the welfare losses under SC are a multiple of the losses under LC or are of a greater order of magnitude.

B. Production functions

I. The first production function is:

$$Q = L[\alpha - \beta(\log L)], L > 1. \quad (8)$$

Under open access, $L = \mathbb{L}/2$, with $U = \frac{1}{2}\left[\alpha - \beta\left(\log\frac{\mathbb{L}}{2}\right)\right]^{1/2}$. The optimal value of L is $L^* = \frac{\mathbb{L}}{2}\left[1 - \frac{\beta}{2\alpha - \beta(1 + 2\log L^*)}\right]$.[18]

As $L = \frac{\mathbb{L}}{2} > 1$, we have $\mathbb{L} > 2$. And $AP_L = \alpha - \beta(\log L) > 0$ implies $L < e^{\alpha/\beta}$. Assume $\alpha = 10$ and $\beta = 2$. Then, $L < e^5 = 148.5$ or $\mathbb{L} < 297$. Thus, $2 < \mathbb{L} < 297$.

For $\mathbb{L} = 3$, $U = 1.5488$, $U^* = 1.5510$, and $\nabla U_3 = -.08$ percent. For $\mathbb{L} = 296$, $\nabla U_{296} = -93.3$ percent. Thus, in percent and absolute value, $.08 < |\nabla U| < 93.3$, with a maximum ratio of $\nabla U_{296}/\nabla U_3 = 1166.3$.

The welfare cost for the central value of $\mathbb{L}$ under LC, HC and SC is (in percent) $\nabla U_{LC} = -4.30$, $\nabla U_{HC} = -17.72$, and $\nabla U_{SC} = -47.80$, i.e., $\nabla U_{SC} = 11.1\nabla U_{LC}$ and $\nabla U_{HC} = 4.1\nabla U_{LC}$. Thus, the welfare cost for $\mathbb{L}$'s central value under SC (HC) is of a greater order of magnitude (a multiple) of that under LC.

[18] As there is no closed solution for L^* $[L^*$ is a function of $\log(L^*)]$, the solution was obtained by 'guessing' a value of L^* (denoted by x), using the related $\log(L^*)$ value in $L^* = \frac{\mathbb{L}}{2}\left[1 - \frac{\beta}{2\alpha - \beta(1 + 2\log L^*)}\right]$ and checking if the solution for L^* (denoted by y) was consistent with the initial guess, i.e., whether $y = x$. If not, the next value of L^* used was between x and y, repeating the exercise until y and x converged.

II. Substituting production function $Q_\lambda = \lambda L(\alpha - \beta L) = \lambda Q, \lambda > 0$ for Q has no impact on L, L^*, m, m^* or ∇x ($x = L, Q, N, U$), i.e., $\nabla x(\lambda\alpha, \lambda\beta) = \nabla x(\alpha, \beta)$, [19] and hence is excluded in what follows. In fact, replacing the production function Q with a monotonically increasing function of Q has no impact on any of the ∇x solutions under autarky, though the same need not hold in the case of international trade.

In conclusion, the results obtained in Section 3.3 that the welfare cost of open access under HC and especially under SC are a multiple or of a greater order of magnitude than those under LC are supported by the results obtained in this section.

4. Trade

This section looks at three scenarios. In order to isolate the issue of externalities associated with different property rights regimes, the first scenario (in Section 4.1) follows Chichilnisky (1994) by assuming a world with two countries, C1 and C2, that are identical except for their property rights (or regulatory regimes, with an open-access common-property regime in C1 and a private property (or regulated) regime in C2. Next, Open access prevails in both C1 and C2 in the second scenario (Section 4.2), with C2's population larger than C1's ($\mathbb{L}_2 > \mathbb{L}_1$). In the third scenario in , C2 does not produce the commodity in the third scenario (Section 4.3).

4.1. <u>Different property rights regime</u>

Chichilnisky (1994) states (p. 855) that "With common property regimes, more is supplied at any given price than is supplied with private property regimes." This is shown in Figure 1 of that paper (p. 857) which depicts the standard low-congestion (LC) case. Similarly, Proposition 1 (p. 857) states: "The common-property supply curve for the resource lies below the private-property supply curve, so that under common-property regimes, more is supplied at a given price. [20] Both supply curves are increasing functions of resource prices."

[19] With $U = m^{1/2}q^{1/2}$, $p = \frac{U_q}{U_m} = AC$, or $\frac{m}{q} = \frac{\mathbb{L}-L}{\lambda L(\alpha-\beta L)} = \frac{1}{\lambda(\alpha-\beta L)}$, i.e., λ cancels out. Thus, as in (3), $L = \frac{\mathbb{L}}{2}$. At the optimum, $\frac{\mathbb{L}-L}{\lambda L(\alpha-\beta L)} = \frac{1}{\lambda(\alpha-2\beta L)}$ and A also cancels out, i.e., it has no impact on L^* (see 4). Thus, λ has no impact on m or m^* either, while q and q^* are multiplied by λ, and U and U^* are multiplied by $\sqrt{\lambda}$. Hence, $\nabla x \equiv (x - x^*)/x^*$ is unaffected by changes in λ.

[20] The common (private) property supply curve is referred to here as the AC (MC) curve.

The paper's new result relates to the impact of trade, where the author states (p. 852) that "… for the country with poorly defined property rights, trade with a country with well-defined property rights increases the overuse of resources and makes the misallocation worse …" As the author shows, trade reduces welfare for the exporting country and worsens its environment as well as the global one.

Similarly, Brander and Taylor (1997) examine a small open economy's trade under LC and open access to a *NR*. They state that trade reduces steady-state utility for a diversified resource exporter and terms-of-trade improvements may be welfare reducing.[21]

I obtain the same results as Chichilnisky (1994) and Brander and Taylor (1997) under both LC and HC. However, the *opposite* holds under SC, in which case trade generates a welfare gain for both countries and an improvement in the international allocation of environmental resources.

Section 4.1.1 provides a graphical analysis, Section 4.1.2 solves the model, Section 4.1.3 presents the simulations.

4.1.1. Graphical analysis

Under LC, the demand curve is D and equilibrium under autarky is at point A for C1 and at point E for C2 in Figure 2. With trade, the price is P_T, with $GF = HG$, i.e., C1's exports equal C2's imports. C2 obtains a welfare gain $\Delta W_2 = EHG$. Since price equals average cost under open access, the producer surplus is always equal to zero and welfare is equal to the consumer surplus. Under autarky, price is P_A and welfare is ZAP_A. Under trade, price is P_T and welfare is ZGP_T. Thus, the impact of trade on welfare is $\Delta W_1 = -P_T GAP_A$. Employment, L, is higher (and thus *NR* is lower) under trade (point F) than under autarky (point A) in C1. The opposite holds for C2 where trade reduces output. Despite the fact that

[21] The model provided here differs from Brander and Taylor's (1997) in three important ways. First, I examine steady-state solutions while they also examine transition paths and the discounted sum of instantaneous utility (or 'welfare'). Second, they assume a small open economy facing exogenously given terms of trade, while these are determined endogenously in this paper. Third, I also examine the results under HC and SC. An interesting analysis of North-South trade's impact on the environment (pollution) – rather than on *NR* – where environmental protection depends on income is Copeland and Taylor (1994).

$MC_1 > MC_2$ (and $NR_1 < NR_2$), output increases in C1 and declines in C2, thereby exacerbating the global distortion in the allocation of NR.

The finding that trade leads to a commodity exporter's welfare loss and worsens the distortion in the global *NR* allocation confirms Chichilnisky's (1994) and Brander and Taylor's (1997) findings. The same result holds in the HC case as C2's (optimal) price is also higher than C1's (open-access) price under autarky. However, in contrast to the LC situation, C1's output declines as employment rises in this case, further raising C1's welfare cost and the international misallocation of *NR* (as output falls in both countries).

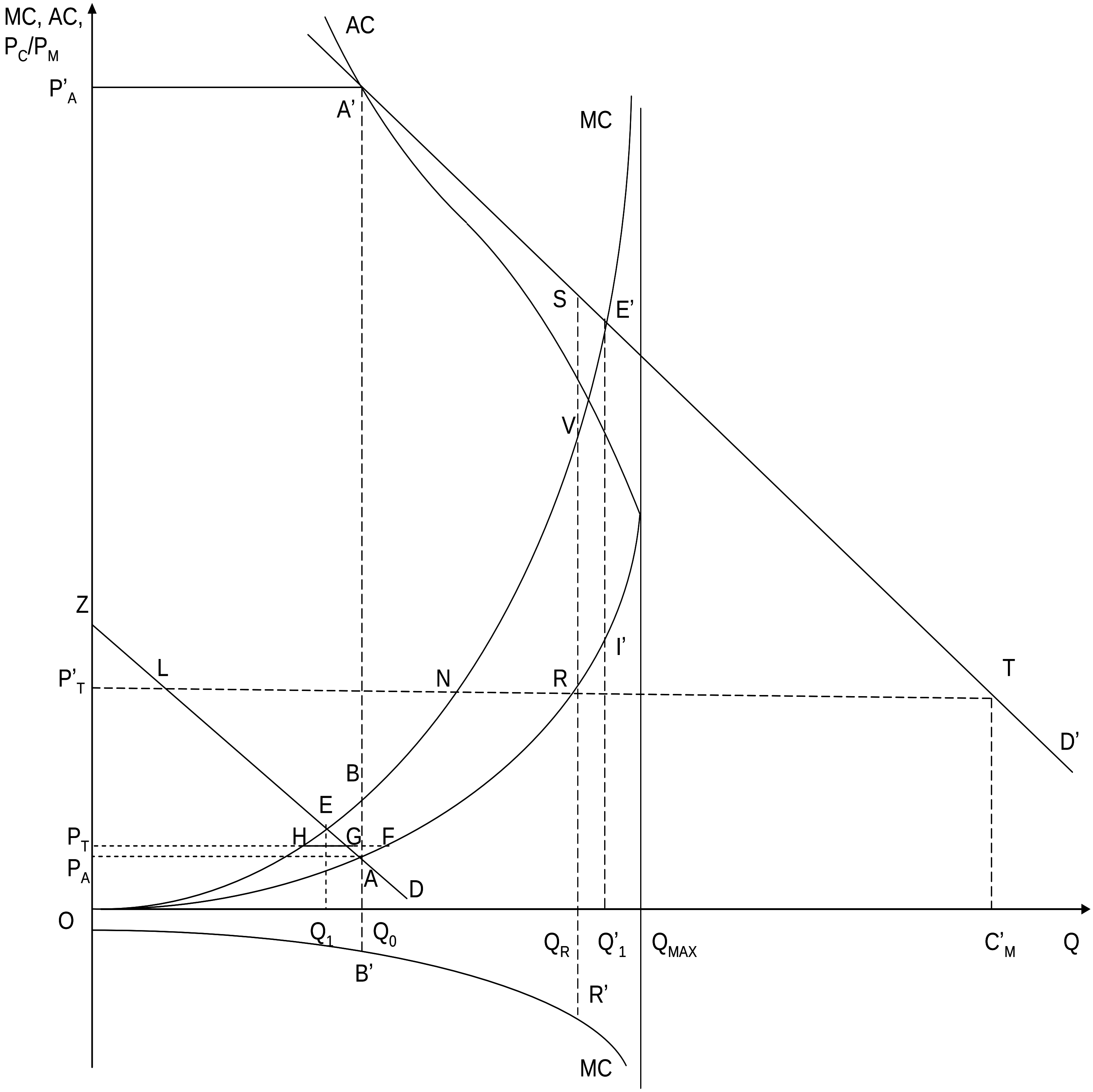
In the SC case, with demand given by D', equilibrium is at A' for C1 and at E' for C2. The autarkic price is higher in open-access C1 than in regulated C2. Hence, C2 exports the commodity to C1, i.e., the direction of trade is reversed, which raises C1's *NR*. Output expands (contracts) in the country with lower (higher) MC (since $MC < 0$ in C1) and lower (higher) AC – represented by point I' (A') – and whose *NR* quality is higher (lower). This improves both the open-access country's and the global *NR* quality or global environment.

Consumption is at point S where the (horizontal) distance between S and the MC curve is equal to the distance between the AC curve and S. The new equilibrium price corresponding to point S is P_S (not shown). Denoting the intersection of the horizontal line from S to the MC curve by X, the welfare gain from trade for C2 is $\Delta W_2 = SXE' > 0$ and the welfare gain for C1 is $\Delta W_1 = P_A' A' S P_S > 0$. Thus, trade improves the global environment and raises global welfare ($\Delta W = \Delta W_1 + \Delta W_2 > 0$) in this case.

4.1.2. <u>Solution</u>

Under trade, price equals average cost in C1 and marginal cost in C2, i.e., $p_T = \frac{1}{\alpha - \beta L_{1T}} = \frac{1}{\alpha - 2\beta L_{2T}^*}$, implying that $L_{1T} = 2L_{2T}^*$. The solution for L_{1T} and L_{2T}^* is:

Figure 2. Trade under Low and High Congestion



MC, AC,
PC/PM
AC
P'A
A'
MC
S
E'
V
Z
I'
L
N
R
T
P'T
D'
B
E
PT
H
G
F
PA
A
D
O
Q1
Q0
QR
Q'1
QMAX
C'M
Q
B'
R'
MC

$$L_{1T} = \frac{2}{5\beta}\left(1.5\alpha + \beta\mathbb{L} - \sqrt{2.25\alpha^2 + \beta^2\mathbb{L}^2 - 2\alpha\beta\mathbb{L}}\right),^{22} \quad L^*_{2T} = \frac{L_{1T}}{2}. \tag{7}$$

Export of Q from C1 is $Q_{1X} = .375\beta L_{1T}(L_I - L_{1T}) \gtreqless 0 \Leftrightarrow L_{1T} \lesseqgtr L_I$,[23] where L_I is the point where AC intersects MC, i.e., the point that separates SC from HC (and where AC exhibits an inflection point).

These results confirm the graphical analysis in the previous section that C1 exports Q under both LC and HC ($L_{1T} < L_I$) and imports M, and it imports Q under SC ($L_{1T} > L_I$) and exports M. In other words, the direction of trade between C1 and C2 is reversed as $L_{1T} = L_I$. The reason is that the inefficiency associated with the negative congestion externality is so large under SC that open-access production costs are larger in C1 than in C2.

4.1.3. Simulation

Table 3 shows the impact of opening up to trade on *NR* and welfare, where $\Delta' U(\Delta' N)$ represents the difference between the value of U (N) under trade and under autarky. Panel A (B) shows results for $\alpha = 10$ (2) and $\beta = 1$. Under autarky, $L_1 \lesseqgtr L_I = \frac{2\alpha}{3} \Leftrightarrow Q_{1S} \gtreqless Q^*_{2S} \Leftrightarrow p_1 \lesseqgtr p^*_2$ (see Section 3). Thus, as long as $L_1 < 2\alpha/3$, $Q_{1S} > Q^*_{2S}$ and $p_1 < p_T < p^*_2$. Once trade occurs, C1 raises its output and exports Q, with an increase in the open-access distortion, and a decline in welfare (as terms-of-trade improvements reduce welfare for an open-access exporting country) and in *NR*. In Panel A, trade reduces C1's welfare if $L_1 < L_I = \frac{2\alpha}{3} = 6.67$ or $\mathbb{L} = 2L_1 < \mathbb{L}_\mathrm{I} = 13.33$. It shows that $\Delta' U_1$ $(\Delta' N_1)$ ranges from -1.47 (-1.68) to -8.39 (-9.6) percent between $\mathbb{L} = 1$ and $\mathbb{L} = 11$.

[22] From $L_{2T} = \frac{L_{1T}}{2}$, we have $Q_S = Q_{1S} + Q_{2S} = L_{1T}(\alpha - \beta L_{1T}) + \frac{L_{1T}}{2}\left(\alpha - \frac{\beta L_{1T}}{2}\right) = L_{1T}(1.5\alpha - 1.25\beta L_{1T})$. Also, $M_{1D} + p_T Q_{1D} = M_{2D} + p_T Q_{2D} = \mathbb{L}$. Given the same relative price p_T and preferences, we have $M_{1D} = M_{2D}$ and $Q_{1D} = Q_{2D}$. Thus, $Q_{1D} = \frac{Q_S}{2} = (.75\alpha - .625\beta L_{1T})L_{1T}$. Also, $\frac{m_{1D}}{q_{1D}} = \frac{M_{1D}}{Q_{1D}} = p_T$ or $M_{1D} = p_T Q_{1D}$. As $M_{1D} + p_T Q_{1D} = \mathbb{L}$, we have $p_T Q_{1D} = M_{1D} = \frac{\mathbb{L}}{2}$. Thus, $Q_{1D} = L_{1T}(.75\alpha - .625\beta L_{1T}) = \frac{M_{1D}}{p_T} = \frac{\mathbb{L}}{2}(\alpha - \beta L_{1T})$, i.e., $1.25\beta L^2_{1T} - (1.5\alpha + \beta\mathbb{L})L_{1T} + \alpha\mathbb{L} = 0$, which implies (7).

[23] Exports of Q from country C1 is $Q_{1X} = Q_{1S} - Q_{1D} = L_{1T}(\alpha - \beta L_{1T}) - (.75\alpha - .625\beta L_{1T})L_{1T} = .25\alpha L_{1T} - .375\beta L^2_{1T} = .375\beta L_{1T}\left(\frac{2\alpha}{3\beta} - L_{1T}\right) = .375\beta L_{1T}(L_I - L_{1T})$, where $L_I = \frac{2\alpha}{3\beta}$.

The opposite occurs for $\mathbb{L} > \mathbb{L}_I = 13.33$ where $Q_{1S} < Q_{2S}$ and $p_2 < p_T < p_1$ (compare points E', S and A' in Figure 2), with trade reducing Q's relative price in C1. This leads C1 to reduce its output and to import Q, resulting in an increase in its welfare. This is shown in Panel A for $\mathbb{L} = 16$ (19), with welfare 20.5 (140) percent higher than under autarky. The negative figures are relatively small because they occur at low $\mathbb{L}$-values, i.e., under LC where the distortion is small. The positive figures occur at high $\mathbb{L}$-values where distortions are large under autarky, and C1's trade-induced decrease in price reduces employment in Q, raising output and consumption, both of which raise welfare.

Table 3. Trade vs. Autarky (Δ') for Open Access (C1) and at Optimum (C2)

Panel A: $\alpha = 10, \beta = 1$

$\mathbb{L}$	Country C1 (Open Access)				Country C2 (Optimum)				C1 + C2			
	N_{1T}	U_{1T}	$\Delta' N_1$ (in %)	$\Delta' U_1$ (in %)	N_{2T}	U_{2T}	$\Delta' N_2^*$ (in %)	$\Delta' U_2^*$ (in %)	N_T	U_T	$\Delta' N$ (in %)	$\Delta' U$ (in %)
1	9.34	1.52	-1.68	-1.47	9.67	1.54	1.65	.41	19.0	3.06	-.01	-.52
6	6.35	1.26	-9.3	-4.75	8.18	1.36	7.97	.74	14.5	2.62	.42	-1.9
11	4.09	.972	-9.1	-8.39	7.05	1.24	8.44	1.0	11.1	2.21	2.0	-3.1
16	2.68	.852	33.8	20.5	6.34	1.11	5.66	4.9	9.02	1.96	14.0	11.7
19	2.14	.849	328	140	6.07	1.05	4.66	5.1	8.21	1.90	88.9	65.4

Panel B: $\alpha = 2, \beta = 1$

$\mathbb{L}$	Country C1 (Open Access)				Country C2 (Optimum)				C1 + C2			
	N_{1T}	U_{1T}	$\Delta' N_1$ (in %)	$\Delta' U_1$ (in %)	N_{2T}	U_{2T}	$\Delta' N_2^*$ (in %)	$\Delta' U_2^*$ (in %)	N_T	U_T	$\Delta' N$ (in %)	$\Delta' U$ (in %)
1	1.38	.587	-8.01	-4.15	1.69	.627	5.62	1.06	3.07	1.21	-.51	-1.46
3	.580	.381	16.0	7.75	1.29	.488	7.5	.615	1.87	.87	10.1	3.74

C2 always gains from trade, though the welfare gains are small relative to either the losses or gains of C1, so that the impact on global welfare (a weighted average of the impacts in C1 and C2) has the same sign as the impact on C1's welfare (despite C2's larger weight since welfare is larger at the optimum than under open access).

Panel B shows that trade reduces (raises) C1's welfare for $\mathbb{L} = 1$ ($\mathbb{L} = 3$) where LC (SC) prevails as $\mathbb{L} = 1 < \widehat{\mathbb{L}} = 2$ ($\mathbb{L} = 3 > \mathbb{L}_{\mathrm{I}} = 2.67$). Thus, the result is the same as in Panel A, i.e., trade's welfare impact for C1 is negative under LC and positive under SC. Also, whether positive or negative, the impact on C1 is greater than that on C2, so that the sign of the impact on global welfare is the same as that on C1's welfare in this case as well.

Lack of effective vaccine against the SRS bacteria in Chile's coastal waters has led Chile to use antibiotics and pesticides at levels that are multiples of those used by Norway, Scotland and British Columbia (Bridsen 2014). Its *NR* endowment quality – i.e., parameter α's level – is thus lower that in these countries. Thus, other things equal, open access' negative impact due to excessive use of variable inputs and loss of output, *NR* and welfare, would be expected to be worse in Chile than in these other countries, as would the impact of trade, a presumption that is supported by the simulation results. For instance, Section 3.4.1 shows that the cost of open access under autarky is (in percent) ∇U_{19} $(\nabla N_{19}) = -.137$ $(-.544)$ for $\alpha = 100$ and -7.056 (-22.3) for $\alpha = 20$. Similarly, trade's impact on C1's welfare cost of open access shown in Panels A and B of Table 3 (in percent) in the case of $\mathbb{L} = 1$ is -1.47 for $\alpha = 10$ and -4.15 for $\alpha = 2$.

Thus, other things equal, optimal regulation and management of the aquaculture industry would be expected to provided larger gains in the case of Chile. In fact, a debate is ongoing about this issue at this point, with meetings between the government and the private sector

4.2. Exporting under SC

The analysis shows that, under SC, an open-access country imports the commodity when trading with a regulated but otherwise identical country. The SC case might thus appear to have little relevance for commodity exporting countries. However, countries differ in a number of ways, with C1 exporting Q to C2 under SC conditions. Assume open access prevails in C1 and that SC prevails under autarky. Then, C1 exports commodity Q in the cases presented below. These are:

i) C2 is more productive than C1 in the production of good M, with $MP_l = w_2 > w_1 = 1$, thereby raising C2's cost of producing Q (which is common for commodity exports from open-access South to regulated North), with autarkic $p_2 = MC_2 > p_1 = AC_1$;

ii) $\mathbb{L}_2 > \mathbb{L}_1$, with C2's demand greater than C1's and autarkic $p_2 = MC_2 > p_1 = AC_1$;
iii) Open access prevails in both countries and C2's demand is larger than C1's (and intersects the AC curve at a point above A$'$ in Figure 2), with $p_2 = AC_2 > p_1 = AC_1$;
iv) C2's endowment of the *NR* is nil (its waters are polluted or otherwise inadequate for aquaculture, or it lacks the type of soil needed for a specific crop), with $Q_2 = 0$;
v) C1 is a small open economy and takes as given the world price, p^*, which intersects the AC curve above C1's autarkic price (above P_A' in Figure 2), i.e., $p^* > p_1$; and
vi) Open access prevails in both countries and C2's externality parameter $\beta_2 > \beta_1$, with $Q_{2T} < Q_{1T}$ and $p_2 = AC_2 > p_1 = AC_1$

Four of the six cases above are examined below.

4.2.1. Open access in C1 and C2, with $\mathbb{L}_2 > \mathbb{L}_1$

As depicted in Figure 2, demand is given by D in C1 and D' in C2. Under autarky, equilibrium is at point A in C1 and A' in C2. Under trade, price is P_T', and C1's excess supply equals C2's excess demand ($\overline{LR} = \overline{RT}$). C1's welfare declines with trade, from ZAP_A to ZLP_T' or by $P_T'LAP_A$ (as does its *NR*), and C2's welfare increases by $P_A'A'TP_T'$.[24] Thus, under open access, trade reduces (raises) a commodity exporter's (importer's) welfare. Also, though $N_2 < N_1$ and $U_2 < U_1$ under autarky, both are equalized under trade ($N_{2T} = N_{1T}$, $U_{2T} = U_{1T}$). Also, $N_1 + N_2 = N_{1T} + N_{2T}$, i.e., global *NR* is unchanged and $U_{2T} = U_{1T}$, with trade resulting in a larger global output ($Q_T^S > Q^S$) and higher global (population-weighted) welfare ($U_T > U$).[25] In the case where C1's demand, D, intersects the AC curve above point V, with the solution in the SC segment of the AC curve.

[24] Though Figure 2 shows aggregate welfare $W_{2T} > W_{1T}$, our interest is in the representative individual's welfare, and with $\mathbb{L}_2 > \mathbb{L}_1$, we have $U_2 < U_1$ and $U_{2T} = U_{1T}$. This is shown in footnote 25.

[25] Utility is $U_i = \frac{1}{2}N_i^{1/2} = \frac{1}{2}\left(\alpha - \beta\frac{\mathbb{L}_i}{2}\right)^{1/2}$ under autarky (i = 1, 2), with $N_1 > N_2$ and $U_1 > U_2$ as $\mathbb{L}_2 > \mathbb{L}_1$. Under trade, $p_T = \frac{1}{\alpha - \beta L_{1T}} = \frac{1}{\alpha - \beta L_{2T}}$, i.e., $L_{1T} = L_{2T}$, and $Q_T^S = Q_{1T}^S + Q_{2T}^S = 2L_{1T}(\alpha - \beta L_{1T})$, $p_T = \frac{M_{iT}^D}{Q_{iT}^D}$, i.e., $p_T Q_{iT}^D = M_{iT}^D$, and $p_T Q_{iT}^D + M_{iT}^D = \mathbb{L}_i$. Thus, $p_T Q_{iT}^D = M_{iT}^D = \mathbb{L}_i/2$. With $Q_T^D = Q_{1T}^D + Q_{2T}^D = Q_T^S$, we have $p_T Q_T^D = p_T Q_T^S = \frac{Q_T^S}{\alpha - \beta L_{1T}} = 2L_{1T}$. Given that $p_T Q_T^D = p_T(Q_{1T}^D + Q_{2T}^D) = \frac{\mathbb{L}_1}{2} + \frac{\mathbb{L}_2}{2} \equiv \overline{\mathbb{L}}$, we have $2L_{1T} = \overline{\mathbb{L}}$, or $L_{iT} = \frac{\overline{\mathbb{L}}}{2}$, i.e., $Q_{iT}^S = \frac{\overline{\mathbb{L}}}{2}\left(\alpha - \beta\frac{\overline{\mathbb{L}}}{2}\right)$. As $Q_{iT}^D = \frac{M_{iT}^D}{p_T} = \frac{\mathbb{L}_i}{2}(\alpha - \beta L_{1T})$, we have $Q_{iT}^D = \frac{\mathbb{L}_i}{2}\left(\alpha - \beta\frac{\overline{\mathbb{L}}}{2}\right)$. Thus, $Q_{iT}^X \equiv Q_{iT}^S - Q_{iT}^D = \left(\frac{\overline{\mathbb{L}}}{2} - \frac{\mathbb{L}_i}{2}\right)\left(\alpha - \beta\frac{\overline{\mathbb{L}}}{2}\right)$. As $\mathbb{L}_2 > \mathbb{L}_1$, we have $\mathbb{L}_1 < \overline{\mathbb{L}} < \mathbb{L}_2$ and $Q_{2T}^X < 0 < Q_{1T}^X$, so C1 (C2) exports Q (M). As $m_i^D = .5$ and $q_{iT}^D = \frac{1}{2}\left(\alpha - \beta\frac{\overline{\mathbb{L}}}{2}\right)$, we have $U_{1T} = U_{2T} = \frac{1}{2}\left(\alpha - \beta\frac{\overline{\mathbb{L}}}{2}\right)^{.5} < U_1$ and $N_{1T} = N_{2T} = \alpha -$

A necessary (sufficient) condition for a SC equilibrium under trade is that it prevails at least in C2 (in both C1 and C2) under autarky. In the latter case, demand D in C1 intersects the AC curve above point V. Trade raises global welfare, reduces (raises) *NR* in C1 (C2), and improves *NR*'s international allocation.

4.2.2. C1 is open access and C2 is regulated, with $\mathbb{L}_2 > \mathbb{L}_1$

Under trade, $p_T = \frac{1}{\alpha - \beta L_{1T}} = \frac{1}{\alpha - 2\beta L_{2T}}$, i.e., $L_{1T} = 2L_{2T}$. The solution for L_{1T} is

$$L_{1T} = \frac{1}{5\beta}\left[3\alpha + \beta(\mathbb{L}_1 + \mathbb{L}_2) - \sqrt{9\alpha^2 + \beta^2}(\mathbb{L}_1 + \mathbb{L}_2)^2 - 4\alpha\beta(\mathbb{L}_1 + \mathbb{L}_2)\right],^{26} \qquad (8)$$

a special case of which is equation (7).

Super congestion occurs for $\mathbb{L}_1 > 13.33.$ Then, $\Delta' U_{1T} = -22.0$ percent for $\mathbb{L}_1 = 14$ and $\Delta' U_{1T} = -11.6$ percent for $\mathbb{L}_1 = 16$. In both cases, $AC_1 < MC_2$ under autarky, so that C1 exports Q. C2 exports M and gains from trade.

4.2.3. C2 specializes in the production of M

In this case, C1 exports Q and imports M. Trade raises Q's relative price – or C1's terms of trade, resulting in a reduction in its welfare and *NR*, and an increase in C2's welfare. Interestingly, the fact that C2 specializes in the production of M leads C1 to specialize in the production of Q, with $M_2^S = \mathbb{L}$ and $L_{1T} = \mathbb{L}$. [27]

$\beta\frac{\bar{\mathbb{L}}}{2} < N_1$. Also, $U_{2T} > U_2$ and $N_{2T} > N_2$, with $N_{1T} + N_{2T} = N_1 + N_2 = 2\alpha - \beta\bar{\mathbb{L}}$: global *NR* is identical under autarky and trade. With $s_i \equiv \frac{\mathbb{L}_i}{\mathbb{L}_1 + \mathbb{L}_2}, s_1 + s_2 = 1$, $s_2 > s_1$, we have $N_{iT} > s_1 N_1 + s_2 N_2$. Thus, $U_T = s_1 U_{1T} + s_2 U_{2T} = \frac{1}{2}\left(\alpha - \beta\frac{\bar{\mathbb{L}}}{2}\right)^{.5} > U = s_1 U_1 + s_2 U_2 = \frac{s_1}{2}{N_1}^{1/2} + \frac{s_2}{2}{N_2}^{1/2} = \frac{s_1}{2}\left(\alpha - \beta\frac{\mathbb{L}_1}{2}\right)^{1/2} + \frac{s_2}{2}\left(\alpha - \beta\frac{\mathbb{L}_2}{2}\right)^{1/2}$, with the result due to concavity and to $N_{iT} > s_1 N_1 + s_2 N_2$ [as $N_{iT} = (N_1 + N_2)/2$ while $s_1 < s_2$ and $N_1 > N_2$, i.e., the larger (smaller) weight multiplies the smaller (larger) *NR* stock]. Thus, trade raises global welfare and equalizes it internationally.

[26] Under trade, $p_T = \frac{1}{\alpha - \beta L_{1T}} = \frac{1}{\alpha - 2\beta L_{2T}}$, i.e., $L_{1T} = 2L_{2T}$. Thus, $Q_T^S = Q_{1T}^S + Q_{2T}^S = L_{1T}(\alpha - \beta L_{1T}) + \frac{L_{1T}}{2}\left(\alpha - \beta\frac{L_{1T}}{2}\right) = L_{1T}(1.5\alpha - 1.25\beta L_{1T})$. From footnote 25, we have $p_T Q_{iT}^D = \frac{\mathbb{L}_i}{2}$. As $p_T Q^D = p_T Q_T^S$, we have $\frac{\mathbb{L}_1 + \mathbb{L}_2}{2} = \frac{L_{1T}(1.5\alpha - 1.25\beta L_{1T})}{\alpha - \beta L_{1T}}$, from which we obtain equation (8).

[27] Total output $Q_{ST} = Q_{1S} = L_{1T}$. As in fn. 22 and 25, $\frac{m_{iD}}{q_{iD}} = \frac{M_{iD}}{Q_{iD}} = p_T$ $(i = 1, 2)$, $M_{iD} = p_T Q_{iD}$, $M_{iD} + p_T Q_{iD} = \mathbb{L}$, $M_{iD} = p_T Q_{iD} = \frac{\mathbb{L}}{2}$ and $m_{iD} = \frac{1}{2}$. Thus, $Q_{iD} = \frac{\mathbb{L}}{2p_T} = \frac{\mathbb{L}}{2}(\alpha - \beta L_{1T})$. Also $Q_{1D} = Q_{2D} = \frac{Q_{ST}}{2}$, so $Q_{iD} = \frac{L_{1T}}{2}(\alpha - \beta L_{1T})$, i.e., $L_{1T} = \mathbb{L}$. Thus, C1 specializes in the production of Q, with $Q_{1S} = \mathbb{L}(\alpha - \beta\mathbb{L})$,

4.2.4. Open access in C1 and C2, with greater negative externality in C2

In this case, $\beta_2 > \beta_1$, with $N_1 > N_2$, $Q_1 > Q_2$, and $U_1 > U_2$ under autarky, and $N_{1T} = N_{2T}$, $Q_{1T} = Q_{2T}$ and $U_{1T} = U_{2T}$ under trade, and global $N > N_T$, $Q > Q_T$, and $U > U_T$.[28] Thus, trade raises global *NR*, output and welfare, and equalizes them internationally, with C1 (C2) exporting $Q(M)$ to C2 (C1), with a decline (rise) in *NR* and welfare in C1 (C2), and C1's greatest *NR* and welfare loss occurring under SC.

5. Application to other issues

The model developed in this paper is relevant to other cases of congestion of natural resources, man-made resources, or other. One case is urban road transport (e.g., Vickery 1969, Small and Verhoef 2007). As Wolshon and Pande (2016) state, there are three fundamental variables in traffic engineering: the number of trips per unit of time or output, Q; the number of cars per unit of distance or car density at a given moment in time, L; and car speed, $N(L), N' < 0$. The quality or productivity of the resource, i.e., the road, is the speed individuals are able to travel on it.

$q_{1S} = \alpha - \beta\mathbb{L}$, and $q_{iD} = \frac{1}{2}(\alpha - \beta\mathbb{L})$. Thus, $U_{iT} = {m_{iD}}^{1/2}{q_{iD}}^{1/2} = \frac{1}{2}(\alpha - \beta\mathbb{L})^{1/2}$. Under autarky, $U_1 = \frac{1}{2}\left(\alpha - \frac{\beta\mathbb{L}}{2}\right)^{1/2}$, i.e., C1's welfare declines because *NR* falls from $N_1 = \alpha - \frac{\beta\mathbb{L}}{2}$ to $N_{1T} = \alpha - \beta\mathbb{L}$. And C2 gains from trade, with $U_2 = 0$ under autarky (as $q_{2D} = q_{2S} = 0$) and $U_{2T} = \frac{1}{2}(\alpha - \beta\mathbb{L})^{1/2}$ under trade.

[28] Assume $\beta_2 = \lambda\beta_1, \lambda > 1$. With open access for C1 and C2, $p_T = \frac{1}{\alpha-\beta_1 L_{1T}} = \frac{1}{\alpha-\beta_2 L_{2T}}$, i.e., $\beta_1 L_{1T} = \beta_2 L_{2T} = \lambda\beta_1 L_{1T}$. Thus, $L_{1T} = \lambda L_{2T}$, and $Q_T^S = Q_{1T}^S + Q_{2T}^S = L_{1T}(\alpha - \beta_1 L_{1T}) + L_{2T}(\alpha - \beta_2 L_{2T}) = (1+\lambda)Q_{2T}^S = (1+\lambda)L_{2T}(\alpha - \beta_2 L_{2T})$. As in fn. 27, $M_{iT}^D + p_T Q_{iT}^D = \mathbb{L}$, $M_{iT}^D = p_T Q_{iT}^D = \frac{\mathbb{L}}{2}$, and $m_{iT}^D = \frac{1}{2}$, $i = 1, 2$. Also, $Q_T^D = Q_{1T}^D + Q_{2T}^D = 2Q_{1T}^D = Q_T^S$, and $2p_T Q_{1T}^D = p_T Q_T^S = (1+\lambda)L_{2T}$. Since $2p_T Q_{1D} = \mathbb{L}$, we have $L_{2T} = \frac{\mathbb{L}}{1+\lambda}$ and $L_{1T} = \frac{\lambda\mathbb{L}}{1+\lambda}$. Thus, $Q_T^S = \mathbb{L}(\alpha - \beta_2 L_{2T})$ and $Q_{iT}^D = \frac{Q_T^S}{2} = \frac{\mathbb{L}}{2}(\alpha - \beta_2 L_{2T}) = \frac{\mathbb{L}}{2}(\alpha - \beta_1 L_{1T})$. C1 exports commodity Q since $Q_{1T}^X = Q_{1T}^S - Q_{1T}^D = \left(\frac{\lambda\mathbb{L}}{1+\lambda} - \frac{\mathbb{L}}{2}\right)(\alpha - \beta_1 L_{1T}) > 0$ as $\frac{\lambda}{1+\lambda} - \frac{1}{2} = \frac{\lambda-1}{2(1+\lambda)} > 0$. Under autarky, $U_1 = \frac{1}{2}\left(\alpha - \frac{\beta_1\mathbb{L}}{2}\right)^{1/2} > U_2 = \frac{1}{2}\left(\alpha - \frac{\lambda\beta_1\mathbb{L}}{2}\right)^{1/2}$, with $U_{iT} = \frac{1}{2}\left(\alpha - \frac{\lambda\beta_1\mathbb{L}}{1+\lambda}\right)^{1/2}$; $N_1 = \alpha - \frac{\beta_1\mathbb{L}}{2} > N_{1T} = \alpha - \frac{\lambda\beta_1\mathbb{L}}{1+\lambda}$; $N_2 = \alpha - \frac{\lambda\beta_1\mathbb{L}}{2} < N_{2T} = \alpha - \frac{\lambda\beta_1\mathbb{L}}{1+\lambda}$; $N = N_1 + N_2 = 2\alpha - (1+\lambda)\frac{\beta_1\mathbb{L}}{2} < N_T = N_{1T} + N_{2T} = 2\alpha - \frac{2\lambda\beta_1\mathbb{L}}{1+\lambda}$ because $\frac{1+\lambda}{2} - \frac{2\lambda}{1+\lambda} = \frac{(\lambda-1)^2}{2(1+\lambda)} > 0$. Also, $Q^S = \frac{\mathbb{L}}{2}\left(\alpha - \beta_1\frac{\mathbb{L}}{2}\right) + \frac{\mathbb{L}}{2}\left(\alpha - \lambda\beta_1\frac{\mathbb{L}}{2}\right) = \frac{\mathbb{L}}{2}\left[2\alpha - (1+\lambda)\beta_1\frac{\mathbb{L}}{2}\right]$. Thus, $Q_T^S - Q^S = \frac{1+\lambda}{4}\beta_1\mathbb{L}^2 - \frac{\lambda}{1+\lambda}\beta_1\mathbb{L}^2 > 0$, as $\frac{1+\lambda}{4} - \frac{\lambda}{1+\lambda} = \frac{(\lambda-1)^2}{4(1+\lambda)} > 0$. Finally, with $U_i = \frac{1}{2}{N_i}^{1/2}$ and $U_{iT} = \frac{1}{2}{N_{iT}}^{1/2}$, it follows that $U_T = U_{1T} + U_{2T} > U = U_1 + U_2$ because $N_T > N$ and because of the concavity of the utility function. Thus, trade under SC (as well as under LC and HC) raises global *NR* and welfare, and equalizes *NR* and welfare across the two countries.

Though Thomps (1998) states that "… the backward-sloping part of the supply curve … is usually referred to in the literature as 'unstable' and ignored as irrelevant ...," the fact is that, as with aquaculture, car density may reach a point where a one percent increase in the number of cars on the road at a moment in time, L, reduces speed by one percent, with output unchanged and equal to its maximum level $Q = \hat{Q}$, with $L = \hat{L}$ (see Section 2.1). Then, a further increase in density – e.g., to the level at peak demand time – would reduce output.

A fire in a closed environment is another case of negative congestion externality. As more people try to escape from a fire, the time needed to do so increases and may reach a point where the number of people who manage to escape per unit of time declines, especially if panic erupts. No tax system exists that will ameliorate a problem that is (perceived to be) one of life or death. On the other hand, optimal regulation, including regular fire drills where people practice exiting a building in an orderly manner, is likely to be useful. This is applicable to other emergency situations where congestion externalities are present (e.g., evacuating a sinking ship).

A similar situation relates to shopping in a limited space, say, a supermarket or department store. An increase in the number of shoppers has two opposite effects on sales: it raises total sales for a given level of sales per shopper, but the greater congestion reduces shoppers' purchases per unit of time. Thus, a congestion level exists – below the level where nobody can move – in which total sales per unit of time fall as the number of shoppers increases, with optimal intervention raising (reducing) output under SC (HC).

The analysis is also relevant for countries with monopoly power on the world commodity market. The negative externality of open access consists of the negative impact of these countries' exports on the world price, their 'natural resource' consists of their international monopoly power, with small-scale growers' marginal revenue MR equal to price p and the countries' $MR < p$. The monopoly's value is equal to the (present value of the) difference between welfare under optimal intervention (e.g., an export tax) and in its absence. The backward-bending segment of the exports' foreign exchange revenue is reached at the point where $MR < 0$. Absence of optimal intervention would drive the value of the country's monopoly resource to zero. This issue is also related to the literature on immiserizing growth (Bhagwati 1958, 1969) though the latter does not hinge on MR being necessarily negative.

6. Policy Implications

Given the significantly greater welfare cost of open access under high congestion (HC) and especially under super congestion (SC), it follows that in countries where HC or SC prevails, regulating the use of the NR would generate gains that are massively larger than found in standard analyses which have dealt with the low-congestion (LC) case.

Such a tax may be hard to levy because of administrative, logistical, enforcement and/or other reasons, more so in developing countries, and especially in remote areas where it is difficult to ascertain the importance of these externalities and/or collect the tax, particularly in the case of small fish farms. Other regulations – as found in developed countries such as Norway and Scotland – designed to minimize these externalities are also likely to be needed, including those regarding the number of licenses allocated, their geographic distribution, selection of qualified applications in accordance with prioritization criteria, etc.[29] Assuming most of the output is exported, it may be optimal to tax exports as the latter is much easier to collect as export points (ports, roads, airports) are limited in number and more easily accessible.

Producers are likely to favor a rise in the sector's terms of trade and so are the authorities, given the increase in employment – often in remote areas where alternatives are limited – and in foreign exchange revenues. However, the country's welfare will decline following a terms of trade increase in the absence of regulation. Thus, an increase in demand raises the importance of a sound, enforceable regulatory framework in order to ensure that the country benefits from the higher prices.

[29] Among other regulations, Norwegian authorities must provide a risk assessment of disease spread in an aquaculture facility and the surrounding environment, including the distance to watercourses and other aquaculture facilities; the type of species to be produced; the farming system and production volume, before giving a license. Also, any license proposal must be made public by the local authorities in the municipality where the farm is to be located and must be published in two local newspapers, allowing the local population to react to the proposal. And an applicant must also obtain a waste discharge permit in order to obtain a license and must provide monthly reports on various aspects of the farm's operation and impact.

7. Concluding Comments

This paper examined the potential impact on output, variable input use, natural resource and welfare of an industry – such as aquaculture – that is based on the exploitation of a natural or other resource where negative congestion externalities play a dominant role. The analysis was conducted under both autarky and trade, and compared outcomes in the case of a common-property resource whose access is open, with the case where it is optimally regulated. This issue is of great importance in a number of developing countries, particularly those characterized by high congestion due to low endowment, high demand or both.

The paper showed that

- The welfare cost of open access under high (HC) and especially under super congestion (SC) is a multiple or orders of magnitude larger than under low congestion (LC) – the case typically examined – and results in a massive waste of resources;
- An optimal tax raises price and reduces output under autarky in the case of LC and HC but *reduces* price and *raises* output under SC,
- A terms-of-trade improvement reduces welfare in an open-access exporting country C1 and reduces its natural resource, *NR*;
- Trade between open-access C1 and regulated but otherwise identical C2 reduces welfare and *NR* in C1 under LC or HC and raises welfare and *NR* under SC;
- Trade between open-access C1 and a non-producing C2 always reduces C1's welfare and *NR*;
- A reduction in *NR* endowment reduces welfare and worsens trade's impact for an exporting country;
- C1's welfare falls with the variable input (labor) level;
- Output and welfare rise with a production tax in an open-access country under SC, and vice versa in the case of a production subsidy.

The possibility of being on the HC or SC segment of the supply curve raises the importance of the optimal management of aquaculture or other industries that are based on the exploitation of an open-access common-property renewable natural resource.

Moreover, producers favor an increase in the price of their product and so does the government, given the positive impact on employment and foreign exchange revenue. However, the government should be aware that the need for a sound, enforceable regulatory framework increases with price because an increase in price in the case of open access results in a decline in welfare, particularly under SC.

References

ADB. 1989. "Project Performance Audit Report, Laguna de Bay Fish Pen Development Project in the Philippines." Asian Development Bank, Manila, Philippines,

Anderson, Ross. 2012 (April 30). "Chilean Fish Farms and the Tragedy of the Commons." *Food Safety News*.

Bajak, Aleszu. 2016. "Chile's Salmon Industry Is Being Strangled by Algae." *Un*dark (March 8). www.undark.org.

Bhagwati, Jagdish N. 1958. "Immiserizing Growth: A Geometrical Note," *Review of Economic Studies* 25 (June): 201-205.

Bhagwati, Jagdish N. 1969. "Optimal Policies and Immiserizing Growth." *American Economic Review* 59 (December): 967−970.

Brander, James A. and M. Scott Taylor. 1997. "International Trade and Open-Access Renewable Resources: The Small Open Economy Case." *Canadian Journal of Economics* 30 (3): 526-552 (August).

Brander, James A. and M. Scott Taylor. 1998. "The Simple Economics of Easter Island: A Ricardo-Malthus Model of Renewable Resource Use." *American Economic Review* 88 (1): 119-138 (March).

Bridson, Peter. 2014. "Atlantic Salmon, Coho Salmon. Chile." *Seafood Report*. Seafood Watch, Monterey.

Chichilnisky, Gabriela. 1994. "North-South Trade and the Global Environment." *American Economic Review* 84 (4): 851-874 (September).

Clark, Colin W. 1990. *Mathematical bio-economics: the optimal management of renewable resources* (2nd edition). Wiley, New York.

Copeland, Brian R. and M. Scott Taylor. 1994. "North-South Trade and the Environment." *Quarterly Journal of Economics* 109 (3): 755-787.

Copeland, Brian R. and M. Scott Taylor. 2005. *Trade and the Environment. Theory and Evidence.* Princeton University Press.

Copes, P. 1970. "The Backward-Bending Supply Curve in the Fishing Industry." *Scottish Journal of Political Economy* 17 (1): 69-77.

Dean, Judith M. 1992. "Trade and the Environment: A Survey of the Literature," in Patrick Low, ed., *International Trade and the Environment*. World Bank Discussion Paper No. 159. Washington, DC: World Bank.

Dey, M.M., F.J. Paraguas, G.B. Bimbao and P.B. Regaspi. 2000. "Technical efficiency of tilapia growout pond operations in the Philippines." *Aquaculture Economics & Management* 4 (1-2): 33-47.

Else, P.K. 1981. “A Reformulation of the Theory of Optimal Congestion Taxes.” *Journal of Transport Economics and Policy*: 217-32 (September).

FAO. 2016. *The State of World Fisheries and Aquaculture*. 2016. Food and Agriculture Organization, Rome.

Gautam, A. B., Ivar Strand and J. Kirkley. 1996. “Leisure/Labor Tradeoffs: The Backward-Bending Labor Supply in Fisheries.” *Journal of Environmental Economics and Management* 31 (3): 352-367.

Gordon, H.S. 1954. “The Economic Theory of a Common Property Resource: The Fishery.” *Journal of Political Economy* 62: 124-42 (April)

Harwell, E. 2010. “Forests in Fragile and Conflict-Affected States. Synthesis Paper.” PROFOR, World Bank (October).

Iliyasu, A., Z.A. Mohamed and R. Terano. 2016. “Comparative analysis of technical efficiency for different production culture systems and species of freshwater aquaculture in Peninsular Malaysia.” *Aquaculture Reports* 3: 51-57 (May).

López, Ramón. 1997. “Environmental Externalities in Traditional Agriculture and the Impact of Trade Liberalization: The Case of Ghana.” *Journal of Development Economics* 53 (1): 17-39.

_____. 1998. “The Tragedy of the Commons in Côte d’Ivoire Agriculture: Empirical Evidence and Implications for Evaluating Trade Policies.” *World Bank Economic Review* 12 (1): 105-31.

Narkiewicz, Adam. 2012 (Jan. 21). “Sole Ownership in Fisheries – A Tentative Reappraisal.” https://ssrn.com/abstract=2342833.

San Diego-McGlone, M.L., Azanza, R.V., Villanoy, C.L. and Jacinto, G.S. 2008. “Eutrophic waters, algal bloom and fish kill in fish farming areas in Bolinao, Pangasinan, Philippines.” *Marine Pollution Bulletin* 57 (6-12): 295-301.

Scott, A. 1955. “The Fishery: The Objective of Sole Ownership.” *Journal of Political Economy* 63: 116-24 (April)

Small, Kenneth A. and Erik T. Verhoef. (2007). *The Economics of Urban Transportation.* Routledge, England.

Stephens, Stanley J. 1998. “Farm Fish Pond Management in California.” *Inland Fisheries – Informational Leaflet* No. 23. Department of Fish and Game, Sacramento, Ca.

Talaue-McManus, Liana. 2006. “Pressures on Rural Coasts in the Asia-Pacific Region.” In Nick Harvey (ed.). *Global Change and Integrated Coastal Management: The Asia-Pacific Region*, pp. 197-230. Springer, The Netherlands.

Thomps, J. M. 1998. “Reflections on the Economics of Traffic Congestion.” *Journal of Transport Economics and Policy* 32, Part I.

Vickery, W. 1969. “Congestion Theory and Transport Investment.” *American Economic Review* 59 (2): 251-60 (May).

Wolshon, Brian and Anurag Pande. 2016. *Traffic Engineering Handbook*, *7th Edition*. Institute of Transportation Engineers. Hoboken, NJ: Wiley & Sons.

Yambot, A.V. 2000. *Problems and issues of Nile tilapia cage farming in Taal Lake, Philippines*. Food and Agriculture Organization, Rome.

Appendix

I. Production tax

Denote the tax rate by τ, with $p = (1 + \tau)p_\tau$, where p_τ is the producer price. The solution for L_τ is $L_\tau = \frac{\mathbb{L}}{2+\tau} < L = \frac{\mathbb{L}}{2}$,[30] i.e., the tax reduces L_τ. This raises (reduces) output and reduces (raises) price p under SC (LC). The tax raises AC. Under SC, it intersects demand curve D' in Figure 1 at a point such as A_1 or A_0, i.e., at a higher output. The impact of τ under HC is more complicated. For instance, an infinitesimal increase in τ raises output. However, the opposite occurs under the optimal tax, as shown below.

The optimal production tax, τ^*, is $\tau^* = \frac{MC-AC}{AC}$. Thus:

$$\tau^* = \frac{1}{\alpha}\left[\sqrt{(\alpha - \beta\mathbb{L})^2 + \alpha\beta\mathbb{L}} - (\alpha - \beta\mathbb{L})\right] = \sqrt{\left(1 - \frac{\beta\mathbb{L}}{\alpha}\right)^2 + \frac{\beta\mathbb{L}}{\alpha}} - \left(1 - \frac{\beta\mathbb{L}}{\alpha}\right).\text{[31]} \quad \text{(1A)}$$

The optimal tax τ^* raises average cost from $AC = \frac{1}{\alpha - \beta L}$ to $AC_\tau = \frac{1+\tau^*}{\alpha-\beta L}$. Under SC, the tax results in an AC curve (in Figure 1) that intersects the demand curve D' at point E', i.e., it raises output. The optimal tax, $\tau^* = E'I'/I'Q_1'$, raises output from Q_0 to Q_1' (and a smaller tax results in an equilibrium at points such as A_0 or A_1 in Figure 1). On the other hand, τ^* reduces output under LC and HC. The optimum is characterized by $MP_L = \alpha - 2\beta L^* > 0$, or $L^* < \frac{\alpha}{2\beta} = \hat{L}, \forall\mathbb{L}$, i.e., the optimum is always in the LC segment of the AC curve. With $\alpha = 10$ and $\beta = 1$, $L^* < \frac{\alpha}{2\beta} = 5, \forall\mathbb{L}$, which implies $N^* = \alpha - \beta L^* > 5$.

Values of $\mathbb{L}$ and corresponding values for τ^* are presented in Table 1A. LC prevails for $\mathbb{L}$ = 1 (4) (9), with $\tau^* = .054$ (.272)(.854). HC prevails for $\mathbb{L}$ =11 ($\tau^* = 1.154$) and SC for $\mathbb{L} = 16$ ($\tau^* = 2$) and 19 ($\tau^* = 2.55$). Thus, for $\mathbb{L} = 19$ (16), τ^* is 47.2 (37) times that for

[30] The consumer price $p = \frac{U_q}{U_m} = \frac{m}{q} = \frac{M}{Q} = \frac{\mathbb{L}-L_\tau}{L_\tau(\alpha-\beta L_\tau)}$. With a producer price p_τ and tax rate τ, the consumer price $p = (1 + \tau)p_\tau$. Under open access, $p_\tau = AC = \frac{1}{\alpha-\beta L_\tau}$. Thus, $p = \frac{1+\tau}{\alpha-\beta L_\tau} = \frac{\mathbb{L}-L_\tau}{L_\tau(\alpha-\beta L_\tau)}$, or $L_\tau = \frac{\mathbb{L}}{2+\tau}$.

[31] The optimal tax $\tau^* = \frac{MC}{AC} - 1 = \frac{\alpha-\beta L^*}{\alpha-2\beta L^*} - 1 = \frac{\beta L^*}{\alpha-2\beta L^*}$. With $L^* = \frac{\mathbb{L}}{2+\tau^*}$, we have $\tau^* = \frac{\beta\mathbb{L}}{(2+\tau^*)\alpha - 2\beta\mathbb{L}}$, or $\alpha{\tau^*}^2 + 2(\alpha - \beta\mathbb{L})\tau^* - \beta\mathbb{L} = 0$, whose solution is equation (1A).

$\mathbb{L} = 1$, 9.4 (7.4) times that for $\mathbb{L} = 4$, and 3 (2.3) times that for $\mathbb{L} = 9$. For $\mathbb{L} = 11$, τ^* is 21.4 times that for $\mathbb{L} = 1$ and 4.2 times that for $\mathbb{L} = 4$.

Table 1A. Optimal Tax Rate $\boldsymbol{\tau}^*$(in %)

$\mathbb{L}$	**A.** $\boldsymbol{\tau}^*(\alpha = 10, \beta = 1)$ **B.** $\boldsymbol{\tau}^*(\alpha = 5, \beta = 1) = \boldsymbol{\tau}^*(\alpha = 10, \beta = 2)$		$\boldsymbol{\tau}^*(\mathbb{L})/\boldsymbol{\tau}^*(1)$	
	A.	**B.**	**A.**	**B.**
1	5.40	11.7	1	1
4	27.2	71.7	5.0	6.1
9	85.4	236	15.8	20.2
11	115.4		21.4	
16	200		37.0	
19	255		47.2	

Under LC (SC), the central value of $\mathbb{L}$ is 5 (16.667), and that of $\tau^* = 36.6$ (212) percent. Thus, the average value of τ^* under SC is 5.8 times the value under LC.

As shown in equation (1A), τ^* can be written as a function of β/α. Hence, the optimal tax for $\alpha = 5, \beta = 1$ is the same as for $\alpha = 10, \beta = 2$. Not surprisingly, as shown in column B, τ^* is larger under a smaller endowment or a greater externality, with τ^* between two and three times the level in column A. Moreover, τ^* rises more rapidly as $\mathbb{L}$ increases.

II. Robustness simulations

This section provides derivations, tables and detailed descriptions of the results provided in Section 3.4 which examines the robustness of the results obtained in Section 3.3 by using different values for the parameters of the production and utility functions, as well as different functional forms for them.

1. Parameter values for α and β

The case of $\alpha = 6, \beta = 1$ is examined in Panel A (where $\mathbb{L} < 12$) and $\alpha = 2, \beta = 1$ (where $\mathbb{L} < 4$) in Panel B. In Panel A, the welfare (*NR*) loss ∇U_{11} (∇N_{11}) for $\mathbb{L} = 11$ is equal to 55 (86) percent or 162 (210) times ∇U_1 (∇N_1) for $\mathbb{L} = 1$, 107 (45) times

∇U_2 (∇N_2), 53 (18) times ∇U_3 (∇N_3), 8.3 (3.4) times ∇U_6 (∇N_6) and 2 (1.5) times ∇U_9 (∇N_9).

Table 2A. Autarky: Open Access vs. Optimum

A: $\alpha = 6, \beta = 1$

$\mathbb{L}$	Open Access L	N	Q	U	Optimum L^*	N^*	Q^*	U^*	Difference: $\frac{x-x^*}{x^*}$ (in %) ∇L	∇N	∇Q	∇U
1	.50	5.5	2.8	1.173	.49	5.5	2.6	1.177	2.7	-.41	2.5	-.339
2	1.0	5.0	5.0	1.118	.90	5.1	4.6	1.124	11	-1.9	8.7	-.516
3	1.5	4.5	6.8	1.061	1.3	4.7	6.0	1.072	19	-4.9	13.3	-1.04
6	3.0	3.0	9.0	.866	2.0	4.0	8.0	.928	50	-25	12.5	-6.65
9	4.5	1.5	6.8	.612	2.4	3.6	8.6	.839	91	-59	-21.4	-27.0
11	5.5	.50	2.8	.350	2.5	3.5	8.8	.784	112	-86	-69	-54.9

B: $\alpha = 2, \beta = 1$

$\mathbb{L}$	Open Access L	N	Q	U	Optimum L^*	N^*	Q^*	U^*	Difference: $\frac{x-x^*}{x^*}$ (in %) ∇L	∇N	∇Q	∇U
1	.50	1.5	.75	.6124	.42	1.6	.67	.6204	18	-4.9	13	-1.6
3	1.5	.50	.75	.3536	.78	1.2	.95	.4845	91	-59	-21	-27

For the average value of ∇U by congestion category, we have ∇U_{SC} $(\nabla U_{HC}) = -41$ (-7.2), or 66.5 (11.7) times $\nabla U_{LC} = -.617$.

Similarly, for the average *NR*, ∇N_{SC} $(\nabla N_{HC}) = -71$ (-28) or 29.6 (11.7)$\nabla N_{LC} = -2.4$.

3. Alternative utility functions

The robustness of the results is examined here under two alternative utility functions.

A. The first utility function specified is (a constant-relative-risk-aversion utility function) $U(x) = \frac{x^{1-\mu}}{1-\mu}$, $\mu \neq 1$ (with $U(x) = \log(x)$ for $\mu = 1$). Assuming separability and $\mu \neq 1$, $U(m, q) = U(m) + U(q) = \frac{m^{1-\mu}}{1-\mu} + \frac{q^{1-\mu}}{1-\mu}$. With $\mu = 1/2$, we have:

$$U = \frac{m^{1/2}}{1/2} + \frac{q^{1/2}}{1/2}. \qquad (2A)$$

Maximizing utility implies that the ratio of marginal utilities equals the commodity's relative price, i.e., $\left(\frac{m}{q}\right)^{1/2} = \left(\frac{M}{Q}\right)^{1/2} = \left[\frac{\mathbb{L}-L}{L(\alpha-\beta L)}\right]^{1/2} = p$. Under open access, $p = AC = \frac{1}{\alpha-\beta L}$. The equation is rewritten as $\beta L^2 - (1+\alpha+\beta\mathbb{L})L + \alpha\mathbb{L} = 0$.[32] The solution is:

$$L = \frac{1}{2\beta}\left(1+\alpha+\beta\mathbb{L} - \sqrt{(1+\alpha+\beta\mathbb{L})^2 - 4\alpha\beta\mathbb{L}}\right). \qquad (3A)$$

At the optimum, $p = \left[\frac{\mathbb{L}-L}{L(\alpha-\beta L)}\right]^{1/2} = MC = \frac{1}{\alpha-2\beta L}$, or $\frac{\mathbb{L}-L}{L(\alpha-\beta L)} = \frac{1}{(\alpha-2\beta L)^2}$, a cubic equation that is rewritten as:

$$4\beta^2 L^3 - \beta(1+4\alpha+4\beta\mathbb{L})L^2 + \alpha(1+\alpha+4\beta\mathbb{L})L - \alpha^2\mathbb{L} = 0. \qquad (4A)$$

Simulation results for $\beta = 1$ are presented in Table 3A, with $\alpha = 6$ in Panel A and $\alpha = 4$ in Panel B.

In Panel A, $\alpha = 6$. LC prevails for $\mathbb{L} = 1$ and $\mathbb{L} = 3$. For $\mathbb{L} = 1$, the welfare impact of open access is $\nabla U_{LC} \equiv \frac{U_{LC}-U_{LC}^*}{U_{LC}^*} = -.19$ percent, and the *NR* impact is $\nabla N_{LC} = \frac{N_L - N_L^*}{N_L^*} = -.93$. For $\mathbb{L} = 3$, the welfare impact of open access is $\nabla U_{L2} = -3.4 = 18\nabla U_{LC}$, the *NR* impact is $\nabla N_{L2} = -14.9 = 16.1\nabla N_{LC}$. The average for $\mathbb{L} = 1$ and $\mathbb{L} = 3$ is $\nabla U_{LC2} = -1.8$ and $\nabla N_{LC2} = -7.9$.

HC prevails for $\mathbb{L} = 5$. In percent, $\nabla U_{HC} = -9.0 = 47\nabla U_{Lc} = 5\nabla U_{LC2}$, and $\nabla N_{HC} = -36.4 = 39\nabla N_{LC} = 5\nabla N_{LC2}$.

SC prevails for $\mathbb{L} = 10$ and $\mathbb{L} = 50$. For $\mathbb{L} = 10$, $\nabla U_{SC} = -21.5 = 113\nabla U_{LC} = 12\nabla U_{LC2}$, and $\nabla N_{SC} = -71.7 = 77\nabla N_{LC} = 9.1\nabla N_{LC2}$. For $\mathbb{L} = 50$, $\nabla U_{S2} = -23.7 = 125\nabla U_{LC} = 13.2\nabla U_{LC2}$ and $\nabla N_{S2} = -95.9 = 103\nabla N_{LC} = 12.1\nabla N_{LC2}$.

[32] Thus, $\left[\frac{\mathbb{L}-L}{L(\alpha-\beta L)}\right]^{1/2} = \frac{1}{\alpha-\beta L} \Rightarrow \frac{\mathbb{L}-L}{L(\alpha-\beta L)} = \frac{1}{(\alpha-\beta L)^2} \Rightarrow \frac{\mathbb{L}-L}{L} = \frac{1}{\alpha-\beta L} \Rightarrow \beta L^2 - (1+\alpha+\beta\mathbb{L})L + \alpha\mathbb{L} = 0.$

With $\mathbb{L} = 5$ (10) (50), L is 71 percent above (twice) (2.1 times) the optimum, with an impact on output of $-5(-43)(-91)$ percent and an impact on *NR* of $-51(-77)(-96)$ percent, amounting to a massive waste of resources.

Table 3A. Autarky: Open Access vs. Optimum

Panel A: $\alpha = 6, \beta = 1$

$\mathbb{L}$	Open Access				Optimum				Difference: $\frac{x-x^*}{x^*}$ (in %)			
	L	N	Q	U	L^*	N^*	Q^*	U^*	∇L	∇N	∇Q	∇U
1	.84	5.2	4.3	5.0	.79	5.2	4.1	5.01	6.1	-.93	5.1	-.19
3	2.4	3.6	8.6	4.3	1.8	4.2	7.5	4.45	33	-15	15	-3.4
5	3.6	2.4	8.6	3.7	2.1	3.9	8.3	4.1	71	-36	-5.1	-9.0
10	5.0	1.0	5.0	2.8	2.5	3.5	8.7	3.6	103	-71	-43	-21
50	5.9	.13	.78	2.1	2.8	3.2	9.0	2.8	111	-96	-91	-24

Panel B: $\alpha = 4, \beta = 1$

$\mathbb{L}$	Open Access				Optimum				Difference: $\frac{x-x^*}{x^*}$ (in %)			
	L	N	Q	U	L^*	N^*	Q^*	U^*	∇L	∇N	∇Q	∇U
1	.76	3.2	2.5	4.1	.68	3.3	2.3	4.1	13	-2.6	9.8	-.46
3	2.0	2.0	4.0	3.5	1.3	2.7	3.5	3.7	55	-26	14	-5.6
5	2.8	1.2	3.4	3.0	1.5	2.5	3.7	3.7	86	-51	-8.5	-12
10	3.5	.53	1.8	2.5	1.7	2.3	3.9	3.1	109	-77	-53	-19
50	3.9	.08	.33	2.1	1.9	2.1	4.0	2.6	112	-96	-92	-20

In panel B, $\alpha = 4$ and $\beta = 1$, with LC (HC) (SC) prevailing for $\mathbb{L} < 4$ ($4 < \mathbb{L} < 5.33$) ($\mathbb{L} > 5.33$). In percent, at $\mathbb{L} = 1$, $\nabla U_{LC} = -.46$ and $\nabla N_{LC} = -2.6$. At $\mathbb{L} = 3$, $\nabla U_{L2} = -5.6 = 12.2\nabla U_{LC}$ and $\nabla N_{L2} = -26.2 = 19\nabla N_{LC}$. At $\mathbb{L} = 5$ (HC), $\nabla U_{HC} = -12.3 = 25.5\nabla U_{LC}$ and $\nabla N_{HC} = -50.9 = 19.6\nabla N_{LC}$. At $\mathbb{L} = 10$ (SC), $\nabla U_{SC} = -19.3 = 42\nabla U_{LC}$ and $\nabla N_{SC} = 78.0 = 30\nabla N_{LC}$. At $\mathbb{L} = 50$, $\nabla U_{S2} = -20.2 = 44\nabla U_{LC}$ and $\nabla N_{S2} = -96.8 = 37\nabla N_{LC}$.

As with the original utility function in (2), the welfare losses under SC are a multiple of those under LC or are of a greater order of magnitude.

B. A second utility function used here as a second check on the results is:

$$U = \left(m - \frac{m^2}{2}\right) + \left(q - \frac{q^2}{2}\right), m = \frac{M}{\mathbb{L}}, q = \frac{Q}{\mathbb{L}}. \quad (5A)$$

Utility maximization implies that $p = \frac{U_q}{U_m} = \frac{1-q}{1-m}$. With $M = l = \mathbb{L} - L$, $m = 1 - \frac{L}{\mathbb{L}}$, and $1 - m = \frac{L}{\mathbb{L}}$. Thus, $p = \frac{1-q}{L/\mathbb{L}} = \frac{(\mathbb{L}-Q)}{L} = \frac{\mathbb{L}}{L} - (\alpha - \beta L)$.

Open Access:

Competitive producers using an open-access *NR* as input select output where $p = AC$, i.e., $p = \frac{1}{\alpha - L}$. Thus, $\mathbb{L} - L(\alpha - \beta L) = \frac{L}{\alpha - \beta L}$, a cubic equation in L, namely:

$$\beta^2 L^3 - 2\alpha\beta L^2 + (1 + \alpha^2 + \beta\mathbb{L})L - \alpha\mathbb{L} = 0. \quad (6A)$$

Optimum:

At the optimum, price $p = MC$, i.e., $\frac{\mathbb{L}}{L} - (\alpha - \beta L) = \frac{1}{\alpha - 2\beta L}$. Thus, we have:

$$\beta^2 L^3 - \frac{3\alpha\beta}{2} L^2 + \frac{1}{2}(1 + \alpha^2 + 2\beta\mathbb{L})L - \frac{\alpha\mathbb{L}}{2} = 0. \quad (7A)$$

Under open access, for $\alpha = 2$ and $\beta = 1$, we have $L^3 - 4L^2 + (5 + \mathbb{L})L - \alpha\mathbb{L} = 0$. For $\mathbb{L} = 1$, an LC case, the solution is $L_L = .4563$, $N_L = 1.544$, $m_L = .544$, and $m_L - \frac{{m_L}^2}{2} = .396$. Also, $q_L = .704$ and $q_L - \frac{q_L^2}{2} = .456$. Thus, $U_L = .8522$.

For the optimum, we have $L^3 - 3L^2 + (5 + 2\mathbb{L})L - \mathbb{L} = 0$, with $L^*_{LC} = .410$, $N^*_{LC} = 1.590$, $q^*_{LC} = .652$, $q^*_{LC} - \frac{(q^*_L)^2}{2} = .440$; $M^*_{LC} = m^*_{LC} = .590$, $m^*_{LC} - \frac{(m^*_L)^2}{2} = .416$ and $U^*_{LC} = .8555 = U_{LC} + .0033$. Thus, the welfare impact of open access is $\nabla U_{LC} = -\frac{.0033}{.8555} = -.00375$ or a loss of .375 percent. The impact on *NR* quality is $\nabla N_{LC} = -2.90$ percent.

For $\mathbb{L} = 5$, a SC case, $L^3 - 4L^2 + 10L - 10 = 0$. Under open access, $L_{SC} = 1.629$, $N_{SC} = .371$, $Q_{SC} = .604$, $q_{SC} = .121$, $M_{SC} = 3.371$, $m_{SC} = .674$, and $U_{SC} = .560$. At the optimum, $L^3 - 3L^2 + 15L - 5 = 0$, $L^*_{SC} = .356$, $N^*_{SC} = 1.644$, $Q^*_{SC} = .585$, $M^*_{SC} = 4.644$, and $U^*_{SC} = .608 = U_{SC} + .048$, with $\nabla U_{SC} = -7.77$ percent, or $20.7\nabla U_{LC}$, and $\nabla N_{SC} = -77.5$ percent, or $26.7\nabla N_{LC}$. Thus, the welfare (*NR*) cost under $\mathbb{L} = 5$ is over 20 (26) times that under $\mathbb{L} = 1$.

For $\mathbb{L} = 10$, also a SC case, $L_{S2} = 1.8$, $N_{S2} = .2$, $U_{S2} = .519$, $L^*_{S2} = .95$, $N^*_{S2} = 1.05$, $U^*_{S2} = .590$ and, in percent, $\nabla U_{SC2} = -12.1 = 32.1\nabla U_{LC}$, and $\nabla N_{SC2} = -81 = 28\nabla N_{LC}$. Thus, the welfare (*NR*) cost under $\mathbb{L} = 10$ is 32 (28) times that under $\mathbb{L} = 1$.

As with the original utility function in (2), the welfare losses under SC are a multiple of the losses under LC or are of a greater order of magnitude.