CENTRAL BANK OF ICELAND

WORKING PAPERS No. 22

SLUGGISH EXIT AND ENTRY OF LABOUR AND CAPITAL, STABILITY AND EFFECTS OF TAXES AND SUBSIDIES IN MODELS OF FISHERIES

by

Asgeir Danielsson

January 2004

CENTRAL BANK OF ICELAND

Economics Department

Central Bank of Iceland Working Papers are published by the Economics Department of the Central Bank of Iceland. The views expressed in them are those of their authors and not necessarily the views of the Central Bank of Iceland.

Also available on the Central Bank of Iceland World Wide Web site (http://www.sedlabanki.is)

ISSN: 1028-9445

SLUGGISH EXIT AND ENTRY OF LABOUR AND CAPITAL, STABILITY AND EFFECTS OF TAXES AND SUBSIDIES IN MODELS OF FISHERIES

by

Asgeir Danielsson*

January 2004

Abstract

It is assumed that exit and entry of fishermen, as well as vessels, is not instantaneous. The wage rate varies with the fortunes of the fishing firms and affects the endogenous labour supply creating a second transmission mechanism from profits to effort. There are realistic cases where this mechanism has important effects on the stability of the dynamic system and on the effects of taxes (subsisdies) on the size of the fish stock. If labour supply depends negatively on the wage rate, the immediate effect of an increase in the tax rate is to increase effort and harvest. In some cases the increase in the tax rate increases overexploitation also in the long term. This outcome is highly probable if the dynamic system is unstable.

Keywords: fisheries management, speed of exit and entry, stability, taxes, subsidies.

JEL Classification: J22, J30, Q22.

---

* I thank Lúðvík Elíasson for helpful comments.

I Introduction

It is commonly assumed in models of commercial fisheries, that the unit prices of inputs are independent of the fortunes of the fishing firms. This is the case in the classical models of Gordon (1954) and Scott (1955) and in the models in Clark (1980 and 1990). In Smith's (1968 and 1969) celebrated dynamic models of commercial fisheries the unit prices of inputs are independent of the fortunes of the fishing firms, but the firms' profits/losses induce gradual entry and exit of firms (vessels). The model in this paper is based on Smith's model. However, it differs from this model in two respects. Firstly, it is allowed that not only capital adjusts gradually, but that the adjustment of labour is also sluggish. This does seem realistic in many cases as lack of alternative employment, sunk cost in acquired labour skills and even attachment to fishermen's "way of life" make fishermen frequently hesitate before leaving the industry.

If labour adjusts sluggishly, it is reasonable to expect that the wage rate deviates temporarily from the market wage in some alternative employment. When the fishery is profitable and new vessels enter, the wage rate increases above the alternative wage rate to attract the required number of fishermen, while if the fishery is making losses, and some vessels are leaving the industry, the wage rate is under pressure and decreases so as to reduce the unemployment of fishermen. In this case the wage rate depends on the profitability of fisheries.

The use of sharing for remunerating the crew, which prevails in most fisheries, makes the unit cost of labour vary with the economic conditions of the firms. In most cases the parameters of the share contracts are rather inflexible and respond sluggishly to excess demand in the market for fishermen's labour. The analysis below covers the case where the fishermen's remuneration is based on a wage rate, which is flexible and responds to the conditions in the market for fishermen's labour, and also the case where the fishermen are paid a share with rigid share parameters.

The second innovation compared to Smith's model is that labour supply is made endogenous. If a change in the wage rate makes it optimal for the fishermen to alter their labour supply it is assumed that this change is met by changing the length of the fishing trip or by changing the intensity of the work.

It will be shown below that allowing the wage rate to change, and allowing the fishermen's supply of labour to respond to these changes in the wage rate, affects the stability of the equilibrium positions of the model. These assumptions also affect how changes in taxes/subsidies affect effort, harvest and the size of the fish stock. In the classical models, where the wage rate is independent of the fortunes of the fishing firms, an increase in a tax on fishing (or a decrease in subsidies to fisheries) lowers the profitability. Effort decreases immediately because losses induce exit of vessels. The size of the stock increases also in the long-term in most cases. In the model in the present paper an increase in the tax rate on fishing reduces the profitability of the fisheries. But the wage rate in the fisheries decreases also. The decrease in profitability induces some exit of firms. However, the decrease in the wage rate may also cause the fishermen that remain in the industry to change their supply of labour. If the decrease in the wage rate induces an increase in the supply of labour, the immediate effect of a discrete increase in the tax rate is an increase in effort and catch and a reduction in the stock size. If the dynamic system is stable, the gradual exit of vessels reduces effort. In most cases this brings the system back to a stable equilibrium where the stock is larger as predicted by the classical models. But if the dynamic system is not stable an increase in the tax rate may lead to serious overfishing and even to a collapse of the stock. These results have obvious consequences for the efficiency of taxes for managing fisheries.†

The paper is organised so that Section II sets out the basic model where, as in Smith's model, capital (number of vessels) adjusts sluggishly. Section III discusses stability of the dynamic system where also labour adjusts sluggishly. In this section it is assumed that the wage rate is perfectly flexible so that there is never any unemployment of labour. Section IV discusses the effects of changes in the tax/subsidy rate. Section V discusses the case where labour is remunerated with a share and Section VI concludes.

II The basic model

All fishermen are assumed identical, each possessing the utility function

$$u = u(c, f, l), \qquad (1)$$

where f is consumption of fish, c is consumption of other goods than fish and l is labour. The fishermen's utility is assumed to depend positively on the consumption of f and c, but negatively on l.

If the price of fish is constant it is reasonable to aggregate f and c into an aggregate consumption bundle. However, if the price of fish varies that aggregation is only approximately valid. In this paper we are studying cases where there are large variations in the supply of fish. It is therefore logical in a general equilibrium model to specify the consumption of this fish in the utility functions. After deriving the relevant formulas below we will point out some conclusions that depend on the

† See Clark (1980 and 1990) on the efficiency of management with taxes. See also Weitzman (2002) for a recent eloquent arguments for the efficiency of using taxes for managing fisheries where there is uncertainty concerning the growth of the fish stock.

assumption that the effect of changes in f are small because f is only a small part of the total consumption. This assumption seems to be realistic in most cases.

The fisheremen are assumed to be price takers in all markets. They decide their consumption of c and f and their supply of l by solving

$$\max_{c,f,l} \; u(c, f, l) \text{ subject to } w_f l = p_c c + p_f f \, . \tag{2}$$

Solving (2) gives consumption of f and c and the supply of l as functions of the relative prices. To simplify the notation the price of c is set as a numéraire, i.e. p_c=1. It is then possible to write the solution for the labour supply as

$$l = l(w_f, p_f) \tag{3}$$

It is not possible to determine the signs of the partial derivatives of the function in (3) on purely theoretical grounds. An increase in w_f makes leisure more expensive and therefore induces substitution from leisure. However, the increase in w_f also increases the fishermen's incomes, which means that if leisure is a normal good the income effect of an increase in w_f is positive. It is the sum of the substitution effect from leisure and the income effect towards increasing leisure that determines the effect of an increase in w_f on the volume of leisure consumed and labour supplied. Similarly, for an increase in p_f, the substitution effect on leisure is positive while the income effect is negative if leisure is a normal good, making the total effect indeterminate.

Let n be the number of identical vessels (firms). The size of the crew is fixed at α_L. The fishing effort of each vessel is determined by the size of the crew and the supply of labour by each fisherman. The crew supplies $\alpha_L l$ units of labour. Given the proper supply of intermediary goods all units of labour are equally efficient. The ratio of intermediary goods to labour is assumed fixed, in which case the volume of intermediary goods used by each vessel in a given period can be written as $\alpha_I l$ where α_I is a constant.

Productivity of fishing effort is assumed to depend on the size of the fish stock. This dependency is described by the non-decreasing function $h(x)$. If $h(x)$ gives the catch of each vessel per unit of labour supplied by the crew, the total catch (H) in each (instant) period is given by

$$H = n \cdot h(x) \cdot l(w_f, p_f) \qquad (4)$$

Smith (1969) pointed out that if there is crowding in the fishing grounds the function h depends negatively on n besides x. This would make the model considerably more complicated and probably give rise to some unexpected dynamics. Following Smith (1969) this possibility will be ignored below.

It was assumed above that, given the size of the stock, the harvest per vessel is proportional to the necessary input of labour and intermediary goods. This assumption contributes to keeping the model simple. It also seems reasonably realistic. However, it does limit somewhat the possible dynamics, e.g. compared to Smith's (1969) model where the firm's marginal cost of fishing is assumed to increase with catch. It is the rapid increases in the marginal cost assumed in the specific examples given in Smith (1969) that create large part of the non-linearity, which gives rise to the varied dynamics.

Given the function for the total harvest in (4) the growth of the fish stock per unit of time ($\dot{x}$) is determined by

$$\dot{x} = G(x) - nh(x)l(w_f, p_f), \qquad (5)$$

where G is a concave function.

The profit function for the individual vessel (firm) is given by

$$\pi = \big((p_f - \tau)h - p_I\alpha_I - w_f\alpha_L\big)l - F\,, \tag{6}$$

where τ is a tax (or subsidy if τ <0) per unit of catch, p_I is the price of intermediary goods and F is the fixed cost per vessel.

A tax per unit of catch is assumed the only special tax on fishing. Price subsidies are a negative tax of this sort. Assuming only one type of tax on fishing is obviously a simplification. Subsidies of fuel and subsidies of capital cost are also frequently observed. It should also be noted that if taxes are used to regulate effort they could be levied on some measure of effort (e.g. fuel), or per vessel, rather than per unit of catch. However, as the results will not change qualitatively if the taxes/subsidies are levied differently, the discussion below will be limited to the case where there is a tax (or subsidy) per unit of catch.

As in Smith (1969) the number of vessels in the fishery is determined by the differential equation

$$\dot{n} = \gamma\pi\,, \tag{7}$$

where γ is a positive constant determining the speed of adjustment. If $\gamma \to \infty$ the adjustment in n has to be instantaneous so that π =0 at all times.

The consequences of allowing that the wage rate in fishing deviates from the alternative wage rate will be explored below. In each case a wage equation, which gives the value of the wage rate in fishing (w_f) at each moment of time, will be specified. The wage equation completes the model. The initial conditions for the state variables, $x(0)$ and $n(0)$, together with the wage equation, the profit equation in (6) and the differential equations in (5) and (7), form a complete system that gives solutions for the state variables, $x(t)$ and $n(t)$, at all times.

The equations

$$G(x) - nh(x)l(w_f, p_f) = 0, \tag{8}$$

and

$$\left(\left(p_f(H) - \tau\right)h - p_I\alpha_I - w_f\alpha_L\right)l - F = 0 \tag{9}$$

give the equilibrium values for x and n. If x_0 and n_0 are solutions to (8) and (9) a first order Taylor-expansion of (5) and (7) around these equilibrium values gives the following system of linear differential equations

$$\dot{n} = \gamma \frac{\partial \pi}{\partial n}(n - n_0) + \gamma \frac{\partial \pi}{\partial x}(x - x_0) \tag{10}$$

and

$$\dot{x} = -h\frac{\partial (nl)}{\partial n}(n - n_0) + \left(\frac{\partial G}{\partial x} - n\frac{\partial (hl)}{\partial x}\right)(x - x_0), \tag{11}$$

that can be used to determine if the equilibrium at (x_0, n_0) is locally stable. The characteristic equation for the system in (10) and (11) is

$$\lambda^2 - T\lambda + \gamma D = 0, \tag{12}$$

where

$$T = \gamma \frac{\partial \pi}{\partial n} + \frac{\partial G}{\partial x} - n\frac{\partial (hl)}{\partial x} \tag{13}$$

is the trace of the coefficient matrix for the dynamic system in (10) and (11), while D is its determinant, i.e.

$$D = \begin{vmatrix} \partial\pi/\partial n & \partial\pi/\partial x \\ -h\,\partial(nl)/\partial n & \partial G/\partial x - n\,\partial(hl)/\partial x \end{vmatrix}. \tag{14}$$

If D is negative, the roots of the characteristic equation are real and have opposite signs. In this case the equilibrium is a saddle point. If D is positive then the real parts of the roots have the same sign. If also T<0, the real parts of the roots are negative, and the equilibrium is locally stable, while if T>0, the real parts of the roots are positive, and the equilibrium is locally unstable.

Comparative statics can be used to study the long-term effects of a change in the tax/subsidy rate (τ) when the dynamic system is stable. Differentiating (8) and (9) totally with respect to n, x and τ gives

$$\frac{\partial \pi}{\partial n} dn + \frac{\partial \pi}{\partial x} dx + \frac{\partial \pi}{\partial \tau} d\tau = 0 \tag{15}$$

and

$$-h \frac{\partial (nl)}{\partial n} dn + \left(\frac{\partial G}{\partial x} - n \frac{\partial (hl)}{\partial x} \right) dx - nh \frac{\partial l}{\partial \tau} d\tau = 0 \tag{16}$$

Solving for the effect of a change in τ on x gives

$$\frac{dx}{d\tau} = \frac{h}{D} \left(n \frac{\partial \pi}{\partial n} \frac{\partial l}{\partial \tau} - \frac{\partial (nl)}{\partial n} \frac{\partial \pi}{\partial \tau} \right). \tag{17}$$

III Sluggish adjustment of labour

Let the sluggish adjustment of labour be determined by the differential equation

$$\dot{m} = \mu \left(w_f - w_o \right), \tag{18}$$

where $\dot{m}$ is the change in the number of fishermen per unit of time, w_o is the wage rate in the alternative employment and μ is a positive constant. If γ, μ and w_f are such that vessels exit faster than fishermen, then the excess supply of labour creates downward pressure on the wage rate in fishing. The decline in w_f reduces the rate of exit of vessels. If w_f is perfectly flexible it adjusts to the value where there is equilibrium between supply and demand for fishermen's labour. If there is equilibrium in the market for fishermen's labour at a given moment in time, this market will remain in equilibrium if α_L fishermen exit for every vessel, i.e. if

$$\alpha_L \dot{n} = \dot{m} \tag{19}$$

Substituting from (6), (7) and (18) into (19), and solving for w_f, gives

$$w_f = w_o + \frac{\gamma\alpha_L}{\mu + \gamma\alpha_L^2 l}\left[\left((p_f - \tau)h - p_I\alpha_I - w_o\alpha_L\right)l - F\right]. \qquad (20)$$

If $\mu \to \infty$, while γ finite, (20) gives that $w_f = w_o$. This is the assumption that has been made in most models of commercial fisheries. At the other extreme, if μ=0, while γ>0, the wage rate must adjust so that there is no exit of vessels to prevent unemployment of fishermen. This happens if

$$w_f = w_o + \frac{1}{\alpha_L l}\left[\left((p_f - \tau)h - p_I\alpha_I - w_o\alpha_L\right)l - F\right]. \qquad (20')$$

In this case $\pi = 0$ at all times.

Substituting from (20) into (6) gives that

$$\pi = \frac{\mu}{\mu + \gamma\alpha_L^2 l}\left[\left((p_f - \tau)h - p_I\alpha_I - w_o\alpha_L\right)l - F\right], \qquad (21)$$

which shows that the sluggish adjustment processes for labour and capital, assumed above, lead to a profit sharing arrangement where the share of each party is determined by γ/μ, i.e. their relative readiness to leave the industry.

Given the wage equation in (19) the model in Section II above is complete. It is possible to show (see Appendix A) that in this case the determinant in (14) is given by

$$D(\gamma,\mu) = \frac{\mu hl}{\mu + \gamma\alpha_L^2 l}\frac{p_f hl}{x}\left\{\frac{\dfrac{\varepsilon_{G,x}}{\varepsilon_{H,p_f}}\left(1 + s_F\varepsilon_{l,p_f}\right) + \dfrac{(p_f - \tau)}{p_f}\varepsilon_{h,x}}{1 - \dfrac{\varepsilon_{l,w_f}}{s_L}\alpha_L l\varphi\left(\dfrac{1}{\varepsilon_{H,p_f}} + s_F\right) - \dfrac{\varepsilon_{l,p_f}}{\varepsilon_{H,p_f}}}\right\}, \qquad (22)$$

where $\varepsilon_{G,x} = \frac{\partial G}{\partial x}\frac{x}{G}$, $\varepsilon_{H,p_f} = \frac{\partial H}{\partial p_f}\frac{p_f}{H}$, $\varepsilon_{l,p_f} = \frac{\partial l}{\partial p_f}\frac{p_f}{l}$, $\varepsilon_{l,w_f} = \frac{\partial l}{\partial w_f}\frac{w_f}{l}$ and $\varepsilon_{h,x} = \frac{\partial h}{\partial x}\frac{x}{h}$ are elasticities and $s_L = \frac{\alpha_L w_l l}{p_f hl}$ and $s_F = \frac{F}{p_f hl}$ are cost shares.

$\varphi = \dfrac{\alpha_L \gamma}{\mu + \gamma \alpha_L^2 l}$, and μ and γ are non-negative. It follows that $0 \leq \alpha_L l \varphi \leq 1$. If μ is large compared to $\gamma \alpha_L^2 l$, then $\alpha_L l \varphi$ is near zero, while if μ is small compared to $\gamma \alpha_L^2 l$, then $\alpha_L l \varphi$ is near unity. In the classical models $\mu \to \infty$, γ is finite, and φ=0.

The elasticity $\varepsilon_{G,x}$ can be negative or positive. If the growth function is strictly concave $\varepsilon_{G,x}$ is positive for $x < x(MSY)$ and negative for $x > x(MSY)$, where $x(MSY)$ is the stock size, which gives the Maximum Sustainable Yield. In the case of the logistic growth function, $G(x) = rx(1 - x/K)$, where r and K are parameters,

$$\varepsilon_{G,x} = \frac{K - 2x}{K - x}. \tag{23}$$

It follows directly from (23) that for possible values of x, i.e. $0 \leq x \leq K$, then $-\infty < \varepsilon_{G,x} \leq 1$.

It is assumed that ε_{H,p_f}<0 and that catch per unit of effort (CPUE) increases with the size of the stock, i.e. $\varepsilon_{h,x}$>0. If $\varepsilon_{H,p_f} \to -\infty$ and $\mu \to \infty$ (and therefore φ=0), then $D(\gamma, \infty)$ is positive. As ε_{l,p_f} is small in realistic cases it is to be expected that $D(\gamma, \mu)$ is positive in most realistic cases.

It is possible to show (see Appendix A) that given the wage equation in (20), T in (13) can be written as

$$T(\gamma, \mu) = \frac{\gamma \mu}{\mu + \gamma \alpha_L^2 l} \left(\frac{\dfrac{1}{\varepsilon_{H,p_f}} \dfrac{p_f h l}{n} \left(1 + s_F \varepsilon_{l,p_f}\right)}{1 - \dfrac{\varepsilon_{l,w_f} \alpha_L l \varphi}{s_L} \left(\dfrac{1}{\varepsilon_{H,p_f}} + s_F \right) - \dfrac{\varepsilon_{l,p_f}}{\varepsilon_{H,p_f}}} \right)$$

$$+\frac{nhl}{x}\left(\varepsilon_{G,x}-\frac{\left(1+\varepsilon_{l,w_f}\alpha_L l\varphi\left(1+\frac{s_I}{s_L}\right)\right)\varepsilon_{h,x}}{1-\frac{\varepsilon_{l,w_f}\alpha_L l\varphi}{s_L}\left(\frac{1}{\varepsilon_{H,p_f}}+s_F\right)-\frac{\varepsilon_{l,p_f}}{\varepsilon_{H,p_f}}}\right), \tag{24}$$

where $s_I = p_I\alpha_I/(p_f h)$ is the share of revenue needed to cover the cost of intermediary goods.

In the classical case where $\mu \to \infty$, and therefore φ=0, $T(\gamma,\infty)$ is negative in most realistic cases. It should though be noted that if also the elasticity of demand for fish is very high ($\varepsilon_{H,p_f} \to -\infty$), the first term on the right hand side in (24) is zero. In this case $T(\gamma,\infty)$ is positive if $\varepsilon_{G,x} > \varepsilon_{h,x}$. As $\varepsilon_{h,x}$>0 this can only happen if the fish stock is overfished, i.e. if $x < x(MSY)$ and $\varepsilon_{G,x}$>0.

The terms on the right hand side in (24), which depend on ε_{l,w_f}, make it possible that the sign of $T(\gamma,\mu)$ is different from the sign of $T(\gamma,\infty)$. The probability that $T(\gamma,\mu)$ is positive, and the dynamic system is unstable, increases when ε_{l,w_f} is large and negative and φ is close to unity because μ is low. Note finally, that it is possible to set μ so low that the second term on the right hand side in (24) determines the sign of $T(\gamma,\mu)$. Increasing μ makes the first term a larger negative number.

IV Changes in the tax rate

Besides affecting the stability of the dynamic system, slow exit and entry of fishermen and endogenous labour supply affects how changes in the tax/subsidy rate (τ) affects the fish stock. Comparative statics can be used to analyse the long-term effect when the dynamic system is stable. Using that if μ>0, then $w_f = w_o$ in the long-term equilibrium, substitution into (17) in Section II gives that (see Appendix A)

$$\frac{dx}{d\tau} = \frac{h^2 l^2}{D(\gamma,\mu)(1-\varepsilon_{l,p_f} \big/ \varepsilon_{H,p_f})} \tag{25}$$

As $D(\gamma,\mu)$>0 and $\left|\varepsilon_{l,p_f}\right|$ is small in realistic cases, the expression in (25) is positive. In these cases, the long-term effect of an increase in the tax rate is to conserve the fish stock.

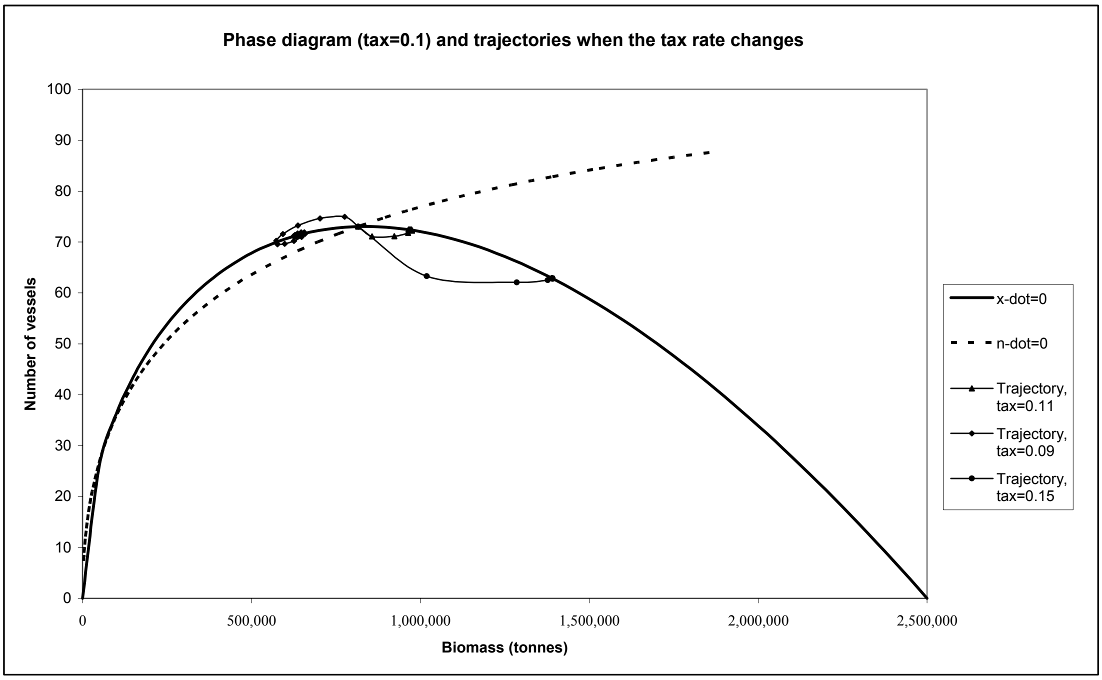
If labour adjusts immediately, i.e. if $\mu \to \infty$, or if the labour supply does not increase when the wage rate decreases, i.e. if $\varepsilon_{l,w_f} \geq 0$, the immediate effect of an increase in the tax rate is a decrease in effort. However, if labour adjusts sluggishly and ε_{l,w_f} <0, the immediate effect of a discrete increase in the tax rate is to increase effort and overfishing through increasing the fishermen's supply of labour. If the dynamic system is stable the increase in the tax rate induces exit of vessels and fishermen, which reduces effort, and the system eventually returns to a stable equilibrium where the stock is larger as predicted by (25). It is though far from certain that this will happen. The impact effect of increasing the supply of labour may be so strong, and the rate of exit of vessels so slow, that an increase in the tax rate will speed up the collapse of the stock. This is especially likely if the dynamic system is unstable.

To illustrate the analytical discussion above, let us consider some possible outcomes of the model. The values of the parameters in these examples have been chosen so that ε_{l,w_f} is negative making instability and unconventional effects of changes in tax/subsidy rates probable. It should though be noted that it is not necessary to search for extreme parmeter values for producing these results. It is not difficult to find realistic parameter values that produce similar, unconventional, results.

The utility function and its parameters are discussed in Appendix C. There, the labour supply function and the demand function for fish are derived. The values of the parmeters of the utility functions have been chosen so that ε_{l,w_f} = -0.46, ε_{H,p_f} =-2 and ε_{l,p_f} =0.0098. In all cases the growth of the fish stock is determined by the logistic growth function with r = 0.56 and K = 2.5 million tonnes. The parameters have been chosen so that the price of fish is 0.388 when the supply of fish is at the maximum sustainable level of 350,000 tonnes. In Figure 1 the isoclines are calculated for the case where the tax rate (τ) is 0.1, the coefficient for the input of intermediary goods (α_I) is 3 and the coefficient for labour (α_L) is 14. It is assumed that $h(x) = qx^{\omega}$. The catchability coefficient (q) is 0.065 and the elasticity of the CPUE with respect to the stock ($\omega = \varepsilon_{h,x}$) is 0.5, the price of intermediary goods (p_I) is 1, the alternative wage (w_o) is 1 and the fixed cost (F) is 100.

The line in Figure 1 marked "x-dot=0" gives the isocline for the values on x and n such that the condition in (8) is met, while the line marked "n-dot=0" gives the isocline in (9). In both cases $w_f = w_o$. Figure 1 shows that the dynamic system has two equilibrium values, one at x = 82,362 tonnes and the other at x = 816,337 tonnes. The first one is locally unstable even in the classical case where labour adjusts immediately and $\mu = \infty$. The second one is locally stable in this case.

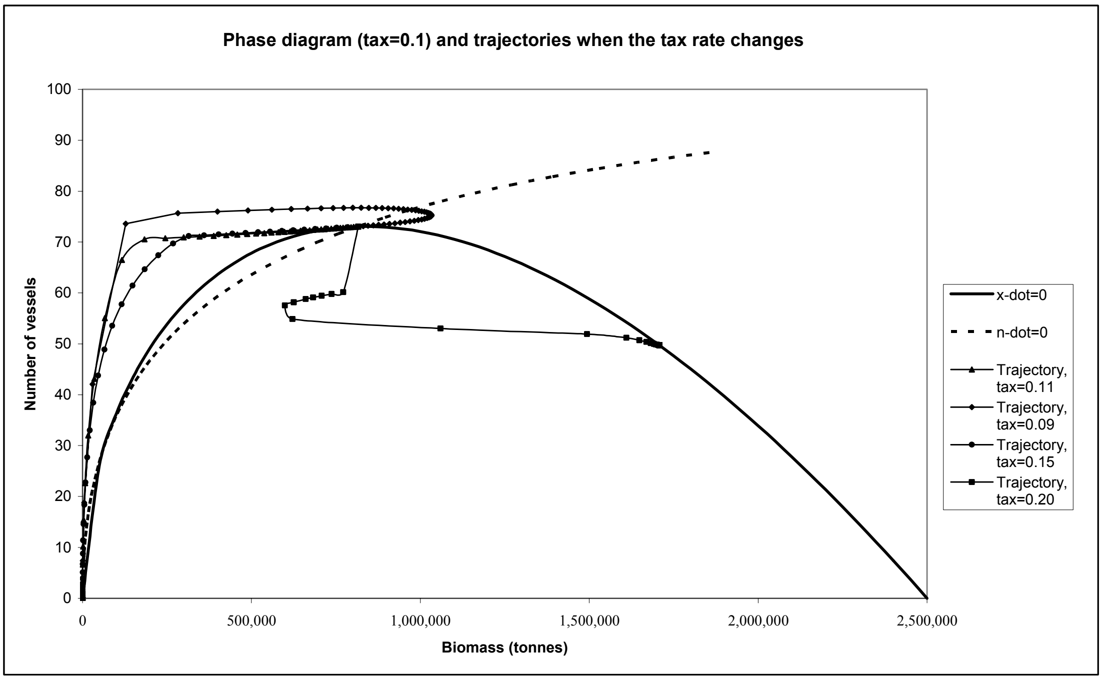
Figure 1



Besides the isoclines, Figure 1 shows some trajectories. The speed of exit and entry of vessels (γ) is 0.01, while the number of fishermen adjusts immediately ($\mu \to \infty$). The trajectories show what happens if the equilibrium is disturbed by a change in the tax rate. The system heads directly for a new stable equilibrium in all cases in spite of the rather low value of γ. When the tax rate is increased the stock size increases and when the tax rate is decreased the stock size decreases. In the case where the tax rate is lowered to τ =0.09, the new equilibrium is a stable focus and the stock declines below the new equilibrium value before eventually reaching the new equilibrium.

Figure 2 shows what happens if the assumption of immediate adjustment of labour is relaxed. In this case μ =10. On the other hand γ has been increased to 1. All other assumptions are the same in Figure 2 as in Figure 1.

Figure 2



All trajectories start at the equilibrium for τ =0.1, i.e. where x =816,337 tonnes. This equilibrium is unstable. The immediate effect of a decrease in the tax rate to τ =0.09 is to decrease effort and catch and therefore to increase the stock size. Gradually effort increases as new vessels enter the fishery which is more profitable because the tax rate has decreased and the size of the fish stock has increased. When the profits decline as the stock size starts to decline, the exit of vessels and fishermen is too slow and the stock collapses.

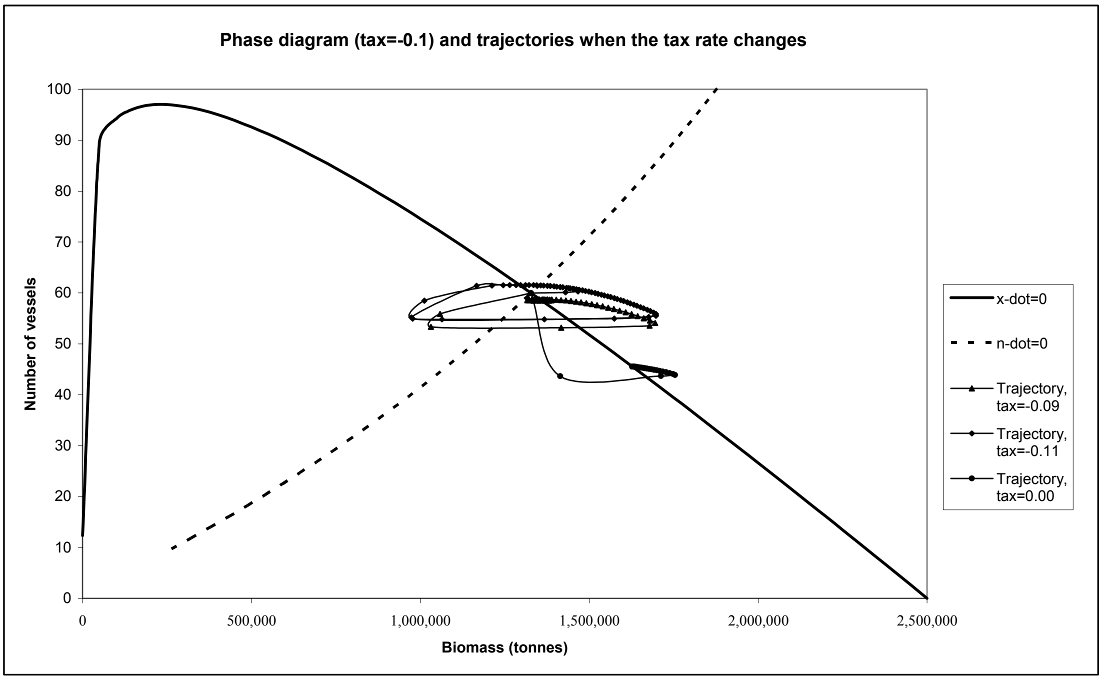
In this case an increase in the tax rate to τ =0.11 or to τ =0.15 does not prevent the stock collapse. Actually the stock collapses faster if τ =0.15 than if τ =0.11 or τ =0.09. However, there must be some increase in the tax rate that is able to prevent the stock collapse. Figure 2 shows that if τ =0.2 the stock will, after a period of decline, return to a stable equilibrium where the size of the stock is 1.7 million tonnes.

In most cases lower values on γ and μ increase the probability that the system is unstable and that a given increase in the tax rate will increase effort and catches in the long-run. The exact values on γ and μ where the system ceases to be stable and becomes unstable depends on the utility function of the fishermen and on the profit function.

It is intuitive that the value on μ where the system becomes unstable (call it $\mu_s(\gamma)$) depends negatively on γ. It is possible to show that this is always the case if γ exceeds some given value. It is also possible to show that μ_s approaches a given value assymtotically when $\gamma \to \infty$. (See Appendix D for a formal discussion.) In the case shown in Figures 1 and 2 this assymptotic value is $\mu_s(\infty)$ = 51.4. In this case the value on μ_s is close to 51.4 when γ is quite low. In this case $\mu_s(1)$ = 51.4, $\mu_s(0.1)$ = 51.7, $\mu_s(0.01)$ = 54.4 and $\mu_s(0.001)$ = 116.3. These numbers can be compared to the number of fishermen which is around 1,000 when the number of vessels (n in Figures 1 and 2) is around 70. If the wage rate in fishing is 10% below the alternative wage rate (w_o = 1) some 5 fishermen, or 0.5% of 1,000 leave the industry in each period when $\gamma \to \infty$.

Figure 3 shows the isoclines and some trajectories in the case where the subsidy rate is τ=-0.1, α_I=20, q=0.00025, $\varepsilon_{h,x}$=0.9 and F=400. It is also assumed that γ=1 and that μ=1. All other assumptions are the same as in Figures 1 and 2.

Figure 3



The only equilibrium in Figure 3 is at 1.33 million tonnes, i.e. well above $x(MSY)$ of 1.25 million tonnes. This equilibrium is unstable, but fairly small decrease in the subsidy rate brings about stability. The trajectory for the case where the subsidy rate is decreased to τ=-0.09 brings the system to a stable equilibrium after a period of considerable overfishing followed by a period of considerably smaller exploitation than the equilibrium exploitation. In this case abolishing all subsidies (τ=0) brings the system fairly fast to a new stable equilibrium with almost no initial decline in the stock, while if the subsidy rate is increased to τ=-0.11 the dynamic system produces a limit cycle.

V The case of sharing

In most parts of the world sharing is used for remunerating labour and capital. This makes the wage rate in most fisheries dependent on the fortunes of the firms. In most cases the parameters of the sharing contracts are fixed over a long period of time and respond slowly to the conditions in the labour market. In this section it is assumed that the sharing parameters are fixed.

The details of the share contracts vary somewhat, but most prescribe that the crew is paid a share of a sum which is calculated as the revenue minus the tax (or plus the price subsidy) and also minus some variable cost items. If σ is the share ratio (per identical crew member), and ρ_I is the share of the cost of the intermediary goods that are shared, the wage rate per unit of labour is

$$w_f = \sigma\left[(p_f - \tau)h - \rho_I p_I \alpha_I\right] . \tag{26}$$

Substituting (26) into (6) and using the resulting expression to calculate the determinant in (14) gives the following expression for the determinant (see Appendix B)

$$D_s = \frac{p_f h^2 l^2 / x}{1 - \frac{1}{\varepsilon_{H,p_f}}\left(\frac{\sigma\alpha_L}{s_L}\varepsilon_{l,w_f} + \varepsilon_{l,p_f}\right)}\left\{\frac{\varepsilon_{G,x}}{\varepsilon_{H,p_f}}\left(1 - \sigma\alpha_L + s_F\left(\frac{\sigma\alpha_L}{s_L}\varepsilon_{l,w_f} + \varepsilon_{l,p_f}\right)\right)\right.$$

$$\left. + \varepsilon_{h,x}\frac{p_f - \tau}{p_f}\left[1 - \sigma\alpha_L + \sigma\alpha_L\varepsilon_{l,w_f}\frac{s_F}{s_L}\right]\right\}. \tag{27}$$

If $\left|\varepsilon_{l,p_f}\right|$ is small, the expression in (26) can be approximated as

$$D_s \approx \frac{p_f h^2 l^2 / x}{1 - \frac{1}{\varepsilon_{H,p_f}}\left(\frac{\sigma\alpha_L}{s_L}\varepsilon_{l,w_f} + \varepsilon_{l,p_f}\right)}\left[\frac{\varepsilon_{G,x}}{\varepsilon_{H,p_f}} + \varepsilon_{h,x}\frac{p_f - \tau}{p_f}\right]$$

$$\cdot\left(1 - \sigma\alpha_L + s_F\frac{\sigma\alpha_L}{s_L}\varepsilon_{l,w_f}\right), \tag{27'}$$

which shows that D_s can be negative if $\left|\varepsilon_{l,p_f}\right|$ is sufficiently small and either $\left[\frac{\varepsilon_{G,x}}{\varepsilon_{H,p_f}} + \varepsilon_{h,x}\frac{p_f - \tau}{p_f}\right]$ or $\left(1 - \sigma\alpha_L + s_F\frac{\sigma\alpha_L}{s_L}\varepsilon_{l,w_f}\right)$ is negative. In these cases the dynamic system is locally unstable.

Substituting from (26) into (6) to calculate the terms in (13) gives that (See Appendix B)

$$T_s(\gamma) = \gamma\frac{p_f hl}{n}\frac{\left((1-\alpha_L\sigma)\frac{1}{\varepsilon_{H,p_f}} + \frac{\varepsilon_{l,w_f}}{\varepsilon_{H,p_f}}\frac{\alpha_L\sigma s_F}{s_L}\right) + s_F\frac{\varepsilon_{l,p_f}}{\varepsilon_{H,p_f}}}{1 - \frac{1}{\varepsilon_{H,p_f}}\left(\sigma\alpha_L\frac{\varepsilon_{l,w_f}}{s_L} + \varepsilon_{l,p_f}\right)}$$

$$+\frac{nhl}{x}\left(\varepsilon_{G,x} - \varepsilon_{h,x}\frac{1+\sigma\alpha_L\frac{(p_f-\tau)}{p_f}\frac{\varepsilon_{l,w_f}}{s_L}}{1-\frac{1}{\varepsilon_{H,p_f}}\left(\sigma\alpha_L\frac{\varepsilon_{l,w_f}}{s_L}+\varepsilon_{l,p_f}\right)}\right). \tag{28}$$

If it is allowed that the share parameters can be fixed in the long term, then it is possible to have a long-term equilibrium where the wage rate in fishing is different from the wage rate in the alternative employment. In this case the comparative static analysis of a change in the tax rate on the size of the stock gives (see Appendix B)

$$\frac{dx}{d\tau} = \frac{h}{D_s}\left(n\frac{\partial\pi}{\partial n}\frac{\partial l}{\partial\tau} - \frac{\partial\pi}{\partial\tau}\frac{\partial(nl)}{\partial n}\right)$$

$$= \frac{h^2l^2}{D_s}\frac{1+\alpha_L\sigma\left(\varepsilon_{l,w_f}\frac{s_F}{s_L} - 1\right)}{1-\frac{1}{\varepsilon_{H,p_f}}\left(\sigma\alpha_L\frac{\varepsilon_{l,w_f}}{s_L}+\varepsilon_{l,p_f}\right)}. \tag{29}$$

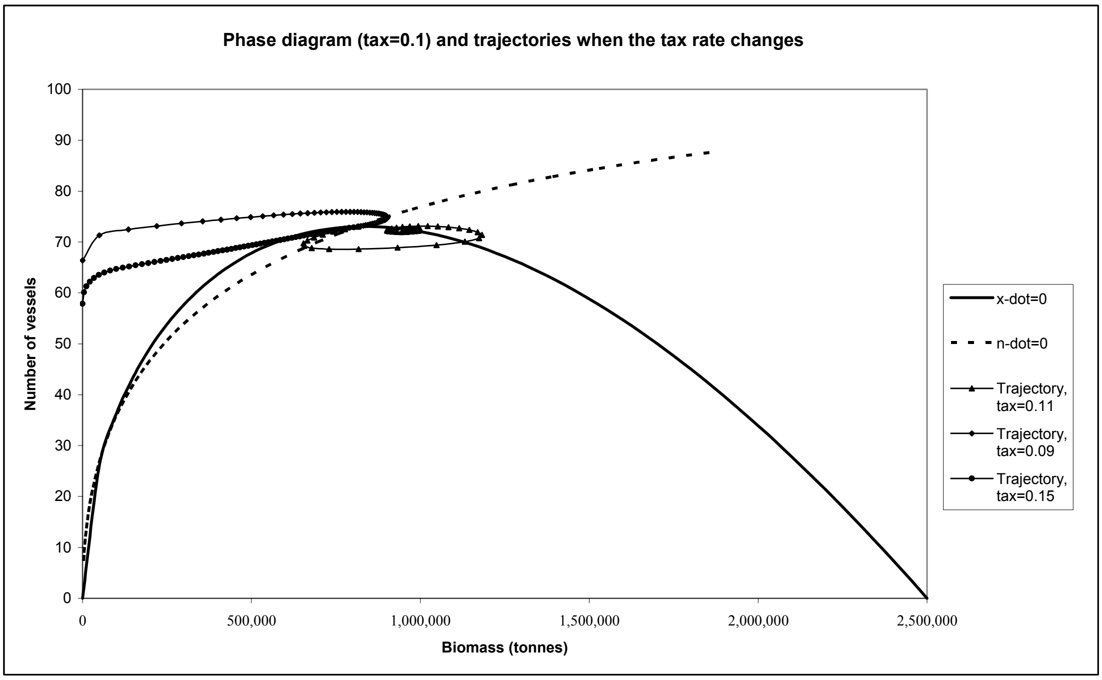
If ε_{l,p_f} is small it is possible to use (27') and substitute from it into (29) to get:

$$\frac{dx}{d\tau} \approx \frac{p_f}{x\left[\dfrac{\varepsilon_{G,x}}{\varepsilon_{H,p_f}} + \varepsilon_{h,x}\dfrac{p_f - \tau}{p_f}\right]}, \tag{29'}$$

which is positive in most realistic cases.

Figure 4 illustrates simulations where there is sharing with fixed parameters but in all other respects the assumptions are the same as in Figure 1 in the previous section. In the simulations in Figure 4 the share ratio is set so that w_f is equal to the alternative wage rate in the equilibrium where the stock size, x, is 816,337 tonnes and τ =0.1. This happens when σ =0.0592 and ρ_l =0.5. The isoclines in Figure 4 are based on the assumption that the share parameters are fixed. In this case the zero-profit isocline is practically identical to the one shown in Figure 1 because $\varepsilon_{l,p_f} / \varepsilon_{H,p_f}$ is near zero. (If ε_{l,p_f} =0 they would be exactly identical). However, the isocline for sustainable catches in Figure 4 differs from the one in Figure 1. The reason is that the equilibrium wage rate varies when the crew is remunerated with a share. Note also that a change in the tax rate affects both isoclines in Figure 4 while it affects only the zero-profit isocline in the case discussed in the previous section where the wage rate is fixed in equilibrium.

Figure 4



The equilibrium in Figure 4 is unstable when γ = 0.01, which is the value used in Figure 1. A slight increase in the tax rate to τ = 0.11 stabilizes the system. The new equilibrium is a stable focus and the system heads for this equilibrium after a period of overfishing followed by a period where the stock is significantly larger than its equilibrium size. A decline in the tax rate to τ =0.09, leads to an initial period where the stock increases, profitability increases and new vessels enter, followed by a period where the stock is overfished so that it collapses. The third trajectory shows what happens if there is a large increase in the tax rate to τ = 0.15. In this case, the stock heads directly towards a collapse.

VI Conclusions

In this paper it has been shown that the assumption concerning the speed of adjustment of the number of fishermen affects significantly the results concerning the stability of equilibrium and concerning the effects of changes in the tax/subsidy rate on the size of the stock. In the model in this paper, the traditional assumption that the wage rate is fixed and the number of fishermen adjusts immediately, gives, in most cases, that the dynamic system is stable. It also gives that an increase in the tax rate (decrease in subsidy rate) leads to a decrease in effort and therefore to an increase in the size of the stock. As the fishermen are assumed to leave the industry immediately when the wage rate is below the alternative wage rate, the incidence of a resource tax, borne by labour, is zero. If it is allowed that the adjustment of the number of fishermen and vessels is less than instantaneous the incidence of a resource tax is zero only in the long-run. The resource tax decreases profits and the wage rate in fisheries for a while. As described above, this decrease in the wage rate may lead the fishermen to increase their supply of labour making taxes a rather inefficient instrument for regulating fisheries. The incidence of the resource tax, borne by fishermen because they hesitate to leave the industry when profits and wage rates decline, creates an additional, political, difficulty for the use of taxes for managing fisheries.

It was pointed out above that a decrease in subsidies to fisheries may lead to an immediate increase in effort. In some cases it also increases overfishing and speeds up the process towards a collapse of the stock. It was also pointed out that there is always some decrease in subsidies/increases in taxes that prevents overfishing. In some cases the increase in tax rates required for preventing overfishing is quite large. And, as in the numerical example in Section V above, where it was assumed that labour was remunerated with a share, it may happen that some increases in the tax rate bring the system to a stable equilibrium with lower rate of exploitation, while a larger increase leads to instability and to the collapse of the stock. In this case there exists a still larger increase in the tax rate that is able to prevent overfishing. This example shows that it is frequently quite difficult to estimate efficient changes in the tax/subsidy rate.

It is also probable that the size of the required changes will make it quite difficult, politically, to implement them.

The results above should not be interpreted as a support for the use of subsidies in fisheries. There is ample evidence of the harmful effects of subsidies in world fisheries. (See e.g. the recent studies done for the OECD by Hannesson, 2001 and Cox, 2002. See also WWF, 2001.) However, the results in this paper show that effort to abolish susbsidies may encounter some serious complications in those cases where there is open access to the fishery. The analysis above indicates that these complications can be avoided if the managers increase the supply of alternative employment and so increase the speed of exit of fishermen. Another possibility is to put direct limitations on the effort or catch of those fishermen that remain in the industry.

Appendix A

Differentiating (20) in Section III at equilibrium values for x and n gives

$$\frac{\partial w_f}{\partial n} = \frac{\alpha_L \gamma}{\mu + \gamma \alpha_L^2 l}\left(\frac{\partial p_f}{\partial H} h^2 \frac{\partial (nl)}{\partial n} l + \frac{F}{l}\frac{\partial l}{\partial n}\right) \tag{A1}$$

$$\frac{\partial w_f}{\partial x} = \frac{\alpha_L \gamma}{\mu + \gamma \alpha_L^2 l}\left(\frac{\partial p_f}{\partial H} hn \frac{\partial (hl)}{\partial x} l + (p_f - \tau) h_x l + \frac{F}{l}\frac{\partial l}{\partial x}\right) \tag{A2}$$

Differentiating (6) in Section II at equilibrium values and using (A1) and (A2) gives

$$\frac{\partial \pi}{\partial n} = \frac{\partial p_f}{\partial H} h^2 \frac{\partial (nl)}{\partial n} l + \frac{F}{l}\frac{\partial l}{\partial n} - \alpha_L l \frac{\partial w_f}{\partial n}$$

$$= \frac{\mu}{\mu + \gamma \alpha_L^2 l}\left(\frac{\partial p_f}{\partial H} h^2 \frac{\partial (nl)}{\partial n} l + \frac{F}{l}\frac{\partial l}{\partial n}\right) . \tag{A3}$$

And

$$\frac{\partial \pi}{\partial x} = \frac{\mu}{\mu + \gamma \alpha_L^2 l}\left(\frac{\partial p_f}{\partial H} hn \frac{\partial (hl)}{\partial x} l + (p_f - \tau) \frac{\partial h}{\partial x} l + \frac{F}{l}\frac{\partial l}{\partial x}\right) \tag{A4}$$

Differentiating (3) in Section II, using (A1) and setting $\varphi = \dfrac{\alpha_L \gamma}{\mu + \gamma \alpha_L^2 l}$ gives

$$\frac{\partial l}{\partial n} = \frac{\partial l}{\partial w_f}\varphi\left(\frac{\partial p_f}{\partial H} h^2 \frac{\partial (nl)}{\partial n} l + \frac{F}{l}\frac{\partial l}{\partial n}\right) + \frac{\partial l}{\partial p_f}\frac{\partial p_f}{\partial H} h \frac{\partial (nl)}{\partial n}$$

$$= \frac{\partial l}{\partial w_f}\varphi\left(\frac{\partial p_f}{\partial H} h^2 l^2 + \frac{\partial p_f}{\partial H} h^2 nl \frac{\partial l}{\partial n} + \frac{F}{l}\frac{\partial l}{\partial n}\right) + \frac{\partial l}{\partial p_f}\frac{\partial p_f}{\partial H} hl + \frac{\partial l}{\partial p_f}\frac{\partial p_f}{\partial H} hn \frac{\partial l}{\partial n} \Rightarrow$$

$$\frac{\partial l}{\partial n} = \frac{\dfrac{\partial p_f}{\partial H} hl \left(\dfrac{\partial l}{\partial w_f}\varphi hl + \dfrac{\partial l}{\partial p_f}\right)}{1 - \dfrac{\partial l}{\partial w_f}\varphi\left(\dfrac{\partial p_f}{\partial H} h^2 nl + \dfrac{F}{l}\right) - \dfrac{\partial l}{\partial p_f}\dfrac{\partial p_f}{\partial H} hn} \tag{A5}$$

Differentiating (3) in Section II and using (A2) gives

$$\frac{\partial l}{\partial x} = \frac{\left(\frac{\partial l}{\partial w_f}\varphi\left(\frac{\partial p_f}{\partial H}hnl + p_f - \tau\right) + \frac{\partial l}{\partial p_f}\frac{\partial p_f}{\partial H}n\right)\frac{\partial h}{\partial x}l}{1 - \frac{\partial l}{\partial w_f}\varphi\left(\frac{\partial p_f}{\partial H}h^2 nl + \frac{F}{l}\right) - \frac{\partial l}{\partial p_f}\frac{\partial p_f}{\partial H}nh} \tag{A7}$$

Using (A1)-(A7) gives:

$$D(\gamma,\mu) = \begin{vmatrix} \partial\pi/\partial n & \partial\pi/\partial x \\ -h\,\partial(nl)/\partial n & \partial G/\partial x - n\,\partial(hl)/\partial x \end{vmatrix}$$

$$= \frac{\mu hl}{\mu + \gamma\alpha_L^2 l}\frac{p_f hl}{x}\left\{\frac{\frac{\varepsilon_{G,x}}{\varepsilon_{H,p_f}}\left(1 + s_F\varepsilon_{l,p_f}\right) + \frac{(p_f - \tau)}{p_f}\varepsilon_{h,x}}{1 - \frac{\varepsilon_{l,w_f}}{s_L}\alpha_L l\varphi\left(\frac{1}{\varepsilon_{H,p_f}} + s_F\right) - \frac{\varepsilon_{l,p_f}}{\varepsilon_{H,p_f}}}\right\} \tag{A8}$$

Using (A1)-(A7) also gives that

$$T(\gamma,\mu) = \gamma\frac{\partial\pi}{\partial n} + \frac{\partial G}{\partial x} - n\frac{\partial(hl)}{\partial x}$$

$$= \gamma\frac{\mu}{\mu + \gamma\alpha_L^2 l}\left(\frac{\partial p_f}{\partial H}h^2\frac{\partial(nl)}{\partial n}l + \frac{F}{l}\frac{\partial l}{\partial n}\right) + \frac{\partial G}{\partial x} - n\frac{\partial(hl)}{\partial x}$$

$$= \frac{\gamma\mu}{\mu + \gamma\alpha_L^2 l}\left(\frac{\frac{1}{\varepsilon_{H,p_f}}\frac{p_f hl}{n}\left(1 + s_F\varepsilon_{l,p_f}\right)}{1 - \frac{\varepsilon_{l,w_f}\alpha_L l\varphi}{s_L}\left(\frac{1}{\varepsilon_{H,p_f}} + s_F\right) - \frac{\varepsilon_{l,p_f}}{\varepsilon_{H,p_f}}}\right)$$

$$+ \frac{nhl}{x}\left(\varepsilon_{G,x} - \frac{\left(1 + \frac{\varepsilon_{l,w_f}}{s_L}\alpha_L l\varphi\left(\frac{(p_f - \tau)}{p_f} - s_F\right)\right)\varepsilon_{h,x}}{1 - \frac{\varepsilon_{l,w_f}\alpha_L l\varphi}{s_L}\left(\frac{1}{\varepsilon_{H,p_f}} + s_F\right) - \frac{\varepsilon_{l,p_f}}{\varepsilon_{H,p_f}}}\right). \tag{A9}$$

Using that in equilibrium $\pi = \left((p_f - \tau)h - p_I\alpha_I - w_f\alpha_L\right)l - F = 0$

$\Rightarrow \frac{p_f - \tau}{p_f} - s_I - s_L - s_F = 0$, where $s_I = \frac{p_I\alpha_I}{p_f h}$. From this it follows that

$$T(\gamma,\mu)=\frac{\gamma\mu}{\mu+\gamma\alpha_L^2 l}\left(\frac{\frac{1}{\varepsilon_{H,p_f}}\frac{p_f hl}{n}\left(1+s_F\varepsilon_{l,p_f}\right)}{1-\frac{\varepsilon_{l,w_f}\alpha_L l\varphi}{s_L}\left(\frac{1}{\varepsilon_{H,p_f}}+s_F\right)-\frac{\varepsilon_{l,p_f}}{\varepsilon_{H,p_f}}}\right)$$

$$+\frac{nhl}{x}\left(\varepsilon_{G,x}-\frac{\left(1+\varepsilon_{l,w_f}\alpha_L l\varphi\left(1+\frac{s_I}{s_L}\right)\right)\varepsilon_{h,x}}{1-\frac{\varepsilon_{l,w_f}\alpha_L l\varphi}{s_L}\left(\frac{1}{\varepsilon_{H,p_f}}+s_F\right)-\frac{\varepsilon_{l,p_f}}{\varepsilon_{H,p_f}}}\right). \tag{A10}$$

If μ>0 then $w_f = w_o$ in equilibrium. In this case $\frac{\partial w_f}{\partial n}=\frac{\partial w_f}{\partial x}=\frac{\partial w_f}{\partial \tau}=0$ and $\frac{\partial l}{\partial \tau}=0$. Using this, and (A5) where φ=0, then (17) in Section II gives that

$$\frac{dx}{d\tau}=\frac{1}{D}\begin{vmatrix}\frac{\partial \pi}{\partial n} & -\frac{\partial \pi}{\partial \tau}\\ -h\frac{\partial(nl)}{\partial n} & nh\frac{\partial l}{\partial \tau}\end{vmatrix}=\frac{1}{D}\left(\frac{\partial \pi}{\partial n}\cdot 0-h\frac{\partial(nl)}{\partial n}(-hl)\right)$$

$$=\frac{1}{D}\frac{h^2l^2}{1-\frac{\partial l}{\partial p_f}\frac{\partial p_f}{\partial H}hn}=\frac{1}{D}\frac{h^2l^2}{1-\varepsilon_{l,p_f}\big/\varepsilon_{H,p_f}} \tag{A11}$$

Appendix B

If there is sharing the wage rate is given by

$$w_f=\sigma\left[(p_f-\tau)h-\rho_I p_I\alpha_I\right] \tag{B1}$$

It follows that

$$\frac{\partial w_f}{\partial n}=\sigma\frac{\partial p_f}{\partial H}h^2\frac{\partial(nl)}{\partial n}, \tag{B2}$$

$$\frac{\partial w_f}{\partial x}=\sigma\left[\frac{\partial p_f}{\partial H}nh\frac{\partial(hl)}{\partial x}+(p_f-\tau)\frac{\partial h}{\partial x}\right], \tag{B3}$$

and $$\frac{\partial l}{\partial n}=\frac{\partial l}{\partial w_f}\frac{\partial w_f}{\partial n}+\frac{\partial l}{\partial p_f}\frac{\partial p_f}{\partial n}$$

$$=\frac{\partial p_f}{\partial H}h\frac{\partial (nl)}{\partial n}\left(\sigma h\frac{\partial l}{\partial w_f}+\frac{\partial l}{\partial p_f}\right) \tag{B4}$$

Eliminating $\frac{\partial l}{\partial n}$ from (B4) gives:

$$\frac{\partial l}{\partial n}=\frac{\frac{\partial p_f}{\partial H}hl\left(\sigma h\frac{\partial l}{\partial w_f}+\frac{\partial l}{\partial p_f}\right)}{1-\frac{\partial p_f}{\partial H}hn\left(\sigma h\frac{\partial l}{\partial w_f}+\frac{\partial l}{\partial p_f}\right)} \tag{B5}$$

In the same way it is possible to get that

$$\frac{\partial l}{\partial x}=\frac{\frac{\partial p_f}{\partial H}n\frac{\partial h}{\partial x}l\left(\sigma h\frac{\partial l}{\partial w_f}+\frac{\partial l}{\partial p_f}\right)+\sigma(p_f-\tau)\frac{\partial h}{\partial x}\frac{\partial l}{\partial w_f}}{1-\frac{\partial p_f}{\partial H}nh\left(\sigma h\frac{\partial l}{\partial w_f}+\frac{\partial l}{\partial p_f}\right)} \tag{B6}$$

Substitution into (14) in Section II and using (B1)-(B6) gives

$$D_s=\begin{vmatrix}\partial\pi/\partial n & \partial\pi/\partial x\\ -h\,\partial(nl)/\partial n & \partial G/\partial x-n\,\partial(hl)/\partial x\end{vmatrix}$$

$$=h\frac{\partial(nl)}{\partial n}\left\{\frac{\partial G}{\partial x}\frac{\partial p_f}{\partial H}\left((1-\sigma\alpha_L)hl+\frac{F}{l}\left(\sigma h\frac{\partial l}{\partial w_f}+\frac{\partial l}{\partial p_f}\right)\right)\right.$$

$$\left.+(1-\sigma\alpha_L)\frac{\partial h}{\partial x}l(p_f-\tau)+\frac{F}{l}\sigma(p_f-\tau)\frac{\partial h}{\partial x}\frac{\partial l}{\partial w_f}\right\}$$

$$=\frac{p_f h^2 l^2/x}{1-\frac{1}{\varepsilon_{H,p_f}}\left(\frac{\sigma\alpha_L}{s_L}\varepsilon_{l,w_f}+\varepsilon_{l,p_f}\right)}\left\{\frac{\varepsilon_{G,x}}{\varepsilon_{H,p_f}}\left(1-\sigma\alpha_L+s_F\left(\frac{\sigma\alpha_L}{s_L}\varepsilon_{l,w_f}+\varepsilon_{l,p_f}\right)\right)\right.$$

$$\left.+\varepsilon_{h,x}\frac{p_f-\tau}{p_f}\left[1-\sigma\alpha_L+\sigma\alpha_L\varepsilon_{l,w_f}\frac{s_F}{s_L}\right]\right\} \tag{B7}$$

If ε_{l,p_f} is small then,

$$D_s \approx \frac{p_f h^2 l^2 / x}{1 - \frac{1}{\varepsilon_{H,p_f}}\left(\frac{\sigma\alpha_L}{s_L}\varepsilon_{l,w_f} + \varepsilon_{l,p_f}\right)}\left[\frac{\varepsilon_{G,x}}{\varepsilon_{H,p_f}} + \varepsilon_{h,x}\frac{p_f - \tau}{p_f}\right]\left(1 - \sigma\alpha_L + s_F\frac{\sigma\alpha_L}{s_L}\varepsilon_{l,w_f}\right) \quad \text{(B7')}$$

Substitution into (13) in Section II and using (B1)-(B6) gives

$$T_s = \gamma\frac{\partial\pi}{\partial n} + \frac{\partial G}{\partial x} - n\frac{\partial(hl)}{\partial x}$$

$$= \gamma\frac{\left((1-\alpha_L\sigma)\frac{\partial p_f}{\partial H}h^2 l^2 + \sigma\frac{\partial p_f}{\partial H}h^2 F\frac{\partial l}{\partial w_f}\right) + F\frac{\partial p_f}{\partial H}h\frac{\partial l}{\partial p_f}}{1 - \frac{\partial p_f}{\partial H}hn\left(\sigma h\frac{\partial l}{\partial w_f} + \frac{\partial l}{\partial p_f}\right)}$$

$$+ \frac{\partial G}{\partial x} - n\frac{l\frac{\partial h}{\partial x} + h\sigma(p_f - \tau)\frac{\partial h}{\partial x}\frac{\partial l}{\partial w_f}}{1 - \frac{\partial p_f}{\partial H}nh\left(\sigma h\frac{\partial l}{\partial w_f} + \frac{\partial l}{\partial p_f}\right)}$$

$$= \gamma\frac{p_f hl}{n}\frac{\left((1-\alpha_L\sigma)\frac{1}{\varepsilon_{H,p_f}} + \frac{\varepsilon_{l,w_f}}{\varepsilon_{H,p_f}}\frac{\alpha_L\sigma s_F}{s_L}\right) + s_F\frac{\varepsilon_{l,p_f}}{\varepsilon_{H,p_f}}}{1 - \frac{1}{\varepsilon_{H,p_f}}\left(\sigma\alpha_L\frac{\varepsilon_{l,w_f}}{s_L} + \varepsilon_{l,p_f}\right)}$$

$$+ \frac{nhl}{x}\left(\varepsilon_{G,x} - \varepsilon_{h,x}\frac{1 + \sigma\alpha_L\frac{p_f - \tau}{p_f}\frac{\varepsilon_{l,w_f}}{s_L}}{1 - \frac{1}{\varepsilon_{H,p_f}}\left(\sigma\alpha_L\frac{\varepsilon_{l,w_f}}{s_L} + \varepsilon_{l,p_f}\right)}\right). \quad \text{(B8)}$$

If it is assumed that the share parameters are fixed in the long run then comparative static analysis gives the effect of a change in the tax on the equilibrium stock size. Substitution into (17) in Section II (and setting $N = 1 - \frac{\partial p_f}{\partial H}hn\left(\sigma h\frac{\partial l}{\partial w_f} + \frac{\partial l}{\partial p_f}\right) = 1 - \frac{1}{\varepsilon_{H,p_f}}\left(\sigma\alpha_L\frac{\varepsilon_{l,w_f}}{s_L} + \varepsilon_{l,p_f}\right)$) gives

$$\frac{dx}{d\tau} = \frac{h}{D_s}\left(n\frac{\partial\pi}{\partial n}\frac{\partial l}{\partial\tau} - \frac{\partial\pi}{\partial\tau}\frac{\partial(nl)}{\partial n}\right)$$

$$= \frac{h^2}{D_s N}\left\{ -l^2\alpha_L\sigma + F\sigma\frac{\partial l}{\partial w_f} + l^2 \right\} = \frac{h^2 l^2}{D_s}\frac{1+\alpha_L\sigma\left(\varepsilon_{l,w_f}\frac{s_F}{s_L} - 1\right)}{1 - \frac{1}{\varepsilon_{H,p_f}}\left(\sigma\alpha_L\frac{\varepsilon_{l,w_f}}{s_L} + \varepsilon_{l,p_f}\right)} \quad \text{(B9)}$$

If ε_{l,p_f} is small then (B7') can be substituting into (B9) to get:

$$\frac{dx}{d\tau} \approx \frac{p_f}{x\left[\frac{\varepsilon_{G,x}}{\varepsilon_{H,p_f}} + \varepsilon_{h,x}\frac{p_f - \tau}{p_f}\right]} . \quad \text{(B9')}$$

Appendix C

The utility function used in the numerical examples is a variant of the CES function

$$U = \left[\delta_1\left(c + af^b - U_0\right)^{-\rho} + \delta_2(l_0 - l)^{-\rho}\right]^{-\frac{1}{\rho}}, \quad \text{(C1)}$$

where $\delta_1 + \delta_2 = 1$. l_0 is the maximum labour time (l) and U_0 is the minimum utility from consuming f units of fish and c units of other consumption goods. a, b and ρ are parameters. The function $c + af^b$ was preferred to the Cobb-Douglas function because the latter behaves unreasonably when the supply of fish is extremely small as is the case when a fish stock collapses.

An individual with the utility function in (C1) must have income so as to be able to buy c and f so that $c + af^b \geq U_0$. For this it must be the case that

$$w_f l_0 \geq p_c\left[U_0 - a(1-b)\left(\frac{p_f}{abp_c}\right)^{\frac{b}{b-1}}\right], \quad \text{(C2)}$$

i.e. the maximum income cannot be lower than the cost of the volumes of c and f that minimise $p_c c + p_f f$ subject to the constraint that $c + af^b \geq U_0$. In the numerical simulations the condition in (C2) has been used to restrict movements in the wage rate. This restriction does not have significant effect on any of the results.

Maximising (C1) subject to the usual budget constraint (cf. (2) in Section II), gives that

$$l = \frac{\left(\frac{\delta_1 w_f}{\delta_2 p_c}\right)^{\frac{1}{\rho+1}} l_0 + \left(1 - \frac{1}{b}\right)\left(\frac{1}{ab}\right)^{\frac{1}{b-1}}\left(\frac{p_f}{p_c}\right)^{\frac{b}{b-1}} + U_0}{\left(\frac{\delta_1 w_f}{\delta_2 p_c}\right)^{\frac{1}{\rho+1}} + \frac{w_f}{p_c}}, \qquad \text{(C3)}$$

Differentiating (C3) with respect to w_f and writing the expression in elasticity form gives:

$$\varepsilon_{l,w_f} = \frac{\frac{1}{\rho+1}\left(\frac{\delta_1 w_f}{\delta_2 p_c}\right)^{\frac{1}{\rho+1}} l_0}{\left(\frac{\delta_1 w_f}{\delta_2 p_c}\right)^{\frac{1}{\rho+1}} l_0 + \left(1 - \frac{1}{b}\right)\left(\frac{1}{ab}\right)^{\frac{1}{b-1}}\left(\frac{p_f}{p_c}\right)^{\frac{b}{b-1}} + U_0} - \frac{\frac{1}{\rho+1}\left(\frac{\delta_1 w_f}{\delta_2 p_c}\right)^{\frac{1}{\rho+1}} + \frac{w_f}{p_c}}{\left(\frac{\delta_1 w_f}{\delta_2 p_c}\right)^{\frac{1}{\rho+1}} + \frac{w_f}{p_c}} \qquad \text{(C4)}$$

Maximisation of (C1) gives also that

$$f = \left(\frac{p_f}{abp_c}\right)^{\frac{1}{b-1}}, \qquad \text{(C5)}$$

which means that $1/(b-1)$ is the elasticity of demand. Aggregating this function over the 100,000 inhabitants, assumed to live and work in the economy, gives the price of fish when p_c is normalised to unity. In the simulations above it was assumed that a = 1.45 and b = 0.5 (and therefore ε_{H,p_f}=-2), l_0=100, U_0=50, δ_1=0.4 and ρ=1. Given these parameter values ε_{l,w_f}=-0.46.

Differentiating (C3) with respect to p_f and writing the expression in elasticity form gives that

$$\varepsilon_{l,p_f} = \frac{\left(\frac{1}{ab}\right)^{\frac{1}{b-1}}\left(\frac{p_f}{p_c}\right)^{\frac{b}{b-1}}}{\left(\frac{\delta_1 w_f}{\delta_2 p_c}\right)^{\frac{1}{\rho+1}} l_0 + \left(1-\frac{1}{b}\right)\left(\frac{1}{ab}\right)^{\frac{1}{b-1}}\left(\frac{p_f}{p_c}\right)^{\frac{b}{b-1}} + U_0} \quad . \tag{C6}$$

Given the parameter values above ε_{l,p_f} =0.0098.

Appendix D

γ and μ affect the coefficients of the characteristic equation (12) in Section 2 above (γD and $-T$). In the expressions for these coefficients in Eqs. (22) and (24) in Section 3 above γ and μ are explicit except that they also affect φ.

Let

$$k = \frac{\gamma\mu}{\mu + \gamma\alpha_L^2 l} \,. \tag{D1}$$

It then follows that

$$\alpha_L l\varphi = \frac{\gamma\alpha_L^2 l}{\mu + \gamma\alpha_L^2 l} = \frac{\gamma - k}{\gamma} \,. \tag{D2}$$

Assume that we are considering values on γ and μ such that Eq. (D1) is valid for a constant k. If γ is sufficiently large changes in γ will have very small effect on $\alpha_L l\varphi$ and therefore a very small effect on γD and $-T$ through changes in $\alpha_L l\varphi$. Eqs. (22) and (24) give that in if $\alpha_L l\varphi$ is treated as a constant and if Eq. (D1) is valid for a constant k, then γD and $-T$ will not change and therefore the roots of the characteristic equation will remain unchanged. Soving for μ in Eq. (D1) gives the value on μ that ensures unchanged sability/instability status of the dynamic system as a function of γ in this case,

$$\mu = \left(1 + \frac{k}{\gamma - k}\right) k \alpha_L^2 l \,. \tag{D3}$$

If the value on μ where the system ceases to be stable for a given value on γ is given by $\mu_s(\gamma)$ and γ is sufficiently large so that $\alpha_L l \varphi$ is approximately constant, then Eqs. (D1) and (D3) can be used to calculate $\mu_s(\gamma)$ for all other sufficiently large values on γ. In the special case where $\gamma \to \infty$ (and $\alpha_L l \varphi$ = 1) Eq. (D3) gives that $\mu_s(\infty) = k\alpha_L^2 l$.

In the case shown in Figures 1 and 2 in Section 4 above $\alpha_L l \varphi$ = 0.965 when γ = 0.1 and $\alpha_L l \varphi$ = 0.996 when γ = 1.0.

References

Björndal, T. and Conrad, J.M., The dynamics of an open access fishery, *Canadian Journal of Economics*, Vol. XX (1): 74-85, February 1987.

D.G. Blanchflower, A.J. Oswald og P. Sanfey, Wages, Profits and Rent-sharing, *Quarterly Journal of Economics*, Vol. CXI: 227-251, 1996.

Clark, C. W. Towards a Predictive Model for the Economic Regulation of Commercial Fisheries. *Can. J. Fish. Aquat. Sci*. 37: 1111-1129, 1980.

Clark, C. W. *Mathematical Bioeconomics, The Optimal Management of Renewable Resources*. A Wiley-Interscience Publication, New York 1990.

Cox, A., *OECD Work on Defining and Measuring Subsidies in Fisheries*, a paper prepared for the OECD workshop on environmentally harmful subsidies, Paris, 7-8 November 2002.

Dixon, H.D., 1987, A Simpel Model of Imperfect Competition with Walrasian features, *Oxford Economic Papers*, 39, 134-60.

Gordon, H.S. (1954), Economic theory of a common property resource: the fishery, *Journal of Political Economy*, 62 (1954): 124-142.

Hannesson, R., Effects of liberalizing trade in fish, fishing vessels and investment in fishing vessels, *OECD Papers Offprint* No. 8, Paris 2001.

Katz, L.F. and Summers, L.H., Industry Rents: Evidence and Implications, *Brooking Paper on Economic Activity, Microeconomics*, 1989.

Economy, 63 (1955): 116-124.

Smith, V., Economics of Production from Natural Resources, *American Economic Review*, vol. LVIII (3), June 1968.

Smith, V., On Models of Commercial Fishing, *Journal of Political Economy*, March/April, 1969.

Weitzman, M., Landing Fees vs. Harvest Quotas with Uncertain Fish Stocks, *Journal of Environmental Economics and Management*, 43 (2), 2002.

Wilen, J., Renewable resource economists and policy: What difference have we made?, *Journal of Environmental Economics and Management*, 39 (2), 2000.

WWF, Hard Facts, Hidden Problems: A Review of Current Data on Fishing Subsidies, WWF Technical Paper, Washington 2001.