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Abstract: Renewable natural resources (like water, fish and wildlife stocks, forests and grazing lands) are critical for the livelihood of millions of people and understanding how they can be managed efficiently is an important economic problem. I show how regulator uncertainty about different economic and ecological parts of the harvesting system affect the optimal choice of instrument for regulating harvesters. I bring prior results into a unified framework and add to these by showing that: 1) quotas are preferred under ecological uncertainty if there are substantial diseconomies of scale in harvesting, 2) that a pro-quota result under uncertainty about prices and marginal costs is unlikely, requiring that the resource growth function is highly concave locally around the optimum and, 3) that quotas are *always* preferred if uncertainly about underlying *structural* economic parameters dominates. These results showing that quotas are preferred in a number of situations qualify the pro fee message dominating prior studies.

JEL: H23, Q2

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1. Introduction

Harvesting commonly owned renewable resources is a classic example of economic activity that calls for public intervention. As early as the beginning of the 19th century, economists have recognised that harvesters of such common pool resources could inflict welfare reducing externalities on each other if they are not subject to appropriate regulation (Warming, 1911)[1]. Today commonly owned renewable natural resources (like water, fish and wildlife stocks, forests, grazing lands, etc) are the foundation of life and income for millions of people across the world. Therefore, understanding how regulations can be designed to ensure efficient resource use is an important economic problem.

Both harvesting costs and resource growth may depend on the size of the resource stock. Thus when one harvester reduces the resource stock through harvesting, he may affect the current harvesting possibilities and costs for other harvesters. He may also affect resource growth and thereby the future harvesting possibilities and costs for other harvesters. Historically, many renewable resources are commonly owned (or even open access) and lack institutions that can ensure proper pricing and the internalization of these effects. This management problem has been addressed, in many cases, by imposing public regulations designed to restrict the size of individual firms' harvest. Such regulations can take many forms ranging from rules about who, when or for how long harvesting can be performed, which harvesting technologies can be used, restrictions on the amount that can be harvest, etc. In most cases, it would be possible to design corresponding fees that give harvesters an incentive to reduce the input or harvest by a quantity equal to the quantitative restrictions set by these rules, but such fees are seldom used in practice (Wilen, 2000). There may be many reasons for this (management tradition, concerns about income distribution, etc.), but in the following, our focus is on management efficiency. Irrespective of other concerns that regulators may have, the social welfare implications of inefficient management can be substantial and should be taken into account. In line with this an obvious question to ask is whether the prevalence of quantitative regulation over price regulation, which we see in practical renewable resource management, is efficient. A number of studies suggest that this may not always be the case and so this is what I consider in the following. I answer the basic question: When should a regulator, who is concerned with efficiency, use a price instrument and when should he use a quantity instrument to regulate a commonly owned renewable resource? For example, should a regulator implement his estimated optimal aggregate level of harvest by setting a harvest fee at the

[1] The original paper in Danish has been translated into English by Andersen (1983),

beginning of the harvest season, or should he at the beginning of the season instead distribute a fixed amount of harvest quotas that harvesters can trade?

A related question has been answered by Weitzman (1974) in a general planning/coordination context. Weitzman considers a regulator who, for example, estimates the optimal aggregate reduction of an externality such as pollution and asks if this reduction should be implemented using an emission fee or tradable emission quotas[2]. Clearly both instruments can implement the optimal reduction with certainty if the regulator is certain about the costs and benefits of reducing emissions. A difference arises if the regulator is uncertain about the costs of reducing emissions. In this case, the regulator would become uncertain about what is the optimal harvest level and also about what level of reduction a given fee would result in. When this is the case, the quota (though still implementing the chosen reduction level with certainty) no longer implements the optimal reduction with certainty. Since lower reduction costs than expected imply that both the optimal reduction and the reduction implemented by the fee instrument are greater than expected, it is not clear which instrument should be preferred (i.e. if the regulator's estimation errors, with respect to the optimal reduction and the reduction resulting from fee regulation, are equal, then the fee would implement precisely the optimal externality reduction). Weitzman derives a simple decision rule for an uncertain regulator implying that the fee is preferred when the reduction cost curve has a steeper slope than the reduction benefit curve around the optimum and the quota is preferred if the reverse is true.

For renewable resource management problems, the costs of reducing externalities are borne by the same group of harvesters who benefit from their reduction and so the cost and benefit curves (as well as the regulator's uncertainty about them) will certainly be correlated. The correlation derives from the fact that harvesters' production possibilities depend on the available stock of the renewable resource, while harvest, at the same time, affects the growth and future availability of this stock. The regulator may be uncertain about the harvester's production technology and the economic environment (so called economic uncertainty) and he may be uncertain about the resource stock (so called ecological uncertainty). Thus, Weitzman's (1974) result does not apply in a straight forward way. Instead regulation of renewable resource harvesters must be studied using models embodying these characteristics.

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[2] Weitzman considers the general planning problem that arises when agents are not coordinated through a market. For example, production plans for different departments within a firm. Another example of a 'missing market' is an externality like pollution, where the planner is a regulator charged with regulating pollution emissions to the optimal level. We present Weitzman's result in this context.

A number of prior studies have done this under various specifications of the harvest and resource growth functions and the regulator's uncertainty. Anderson (1986), Androkovich and Stollery (1991), Jensen and Vestergaard (2003), and Hansen (2008) investigate instrument choice when resource growth is very fast compared to the fluctuations in the natural and economic environment that cause regulator uncertainty. Focusing on this particular class of renewable resources allows these authors to assume that the stock is always in a steady state equilibrium (because the dynamic adaption path towards equilibrium happens so fast that it can be ignored). This facilitates the analysis, but as e.g. Anderson (1986) recognizes, this is also a restrictive assumption that reduces the general applicability of the derived results.

Weitzman (2002) generalizes the analyses of instrument choice to the dynamic setting using a stock-recruitment model. This model is relevant for a much broader class of renewable resources, including those where growth dynamics are relatively slow. For resources with slow growth, the welfare effects of instrument choice during transition to equilibrium cannot be ignored. Because of this information feedback and adjustments of the regulatory instrument during the transition become important and should be taken into account. The model developed by Weitzman (2002) makes this possible by using a detailed and explicit representation of interactions and how they depend on regulator uncertainty. With this model, Weitzman (2002) investigates which instrument is preferred when the regulator is uncertain about the size of the available resource stock at the beginning of each harvesting season (i.e when there is so called ecological uncertainty), but is certain about the harvester's production technology and other economic conditions (so there is no so called economic uncertainty). He finds that in this situation, fees are always the preferred instrument. Hannesson and Kennedy (2005) extend this analysis to also include economic uncertainty using a simulation model constructed as a specific functional representation of the theoretical model developed by Weitzman. When the regulator has ecological uncertainty, Hannesson and Kennedy also find that fees are the preferred instrument. However, when the regulator has is uncertain about output prices,[3] they find that the quota instrument may be preferred for some combinations of parameter values of their simulation model[4].

[3] Hannesson and Kennedy investigate the implications of regulator uncertainty about the output price and 'availability' of the resource (the marginal cost of harvesting which may be influenced by fluctuating climate and weather conditions). This is what I in the following call variable economic uncertainty.

[4] In addition to Hannesson and Kennedy (2005), for example Hansen et al (2008) use a dynamic model to investigate instrument choice when the main source of regulator uncertainty is about the extent of the illegal harvest and non-compliance with regulations. While this may be relevant for some fisheries and perhaps also other resource regulation problems, I ignore this type of uncertainty here and assume that compliance is not a major problem.

In this paper, my point of departure from the literature is the formal model developed by Weitzman (2002). I extend this study of ecological uncertainty by incorporating economic uncertainty and by allowing economies of harvesting scale[5] .

Technical economies and diseconomies of scale in harvesting may be important in industries operating either substantially below or close to harvesting capacity. In addition market diseconomies of scale may be quite important for resource industries supplying local markets[6]. Here increasing harvest will systematically reduce the output price as market equilibrium moves down the demand curve.

I incorporate two types of economic uncertainty. The first type, called variable economic uncertainty, captures uncertainty about the output price and the effects of variations in input prices and. climate on marginal harvesting costs in the coming harvest season. Such uncertainty is common in natural resource industries where e.g output prices may fluctuate substantially over short periods of time. These effects vary from one harvesting season to another and affect harvesters by shifting the marginal profit of harvesting. This is the type of economic uncertainty simulated by Hannesson and Kennedy (2005). The second type of economic uncertainty, called structural economic uncertainty, captures basic estimation uncertainty that the regulator has about the structural parameters which characterize the harvester's technology and profit function. Unlike variable economic uncertainty which reflects real shifts in harvesting conditions that occur after the regulator fixes regulations, structural economic uncertainty only reflects regulator uncertainty about the harvesting industries basic profit function parameters. Since regulators typically do not know these parameters, but must estimate them, they will often be uncertain about their precise value. In practice, a regulator's uncertainty about the industry's profit function parameters may be just as important as his uncertainty about resource stock estimates (ecological uncertainty) or his uncertainty about how variable economic conditions like input and output prices will develop. Yet this type of uncertainty has not been investigated in this context.

The main contribution of this paper is that I from a general model of resource harvesting derive a single equation or rule showing how the welfare implications of the two regulatory instruments depend on all three types of uncertainty. The rule is derived from a dynamic model under rather general assumptions, yet it is still relatively simple and facilitates interpretation and practical application. This is possible because I apply second order approximations of the

[5] Weitzman(2002) as well as Hannesson and Kennedy(2005) assume no economies of scale
[6] Thanks to Rögnvaldur Hannesson for drawing my attention to this effect.

underlying functions. I argue that this approximation captures the main effects and that higher order approximations are often infeasible in practical regulatory settings.

When marginal profit does not depend on the resource stock (see e.g. Hannesson and Kennedy (2005)) non-concavity of the marginal profit function may render fees ineffective as a regulatory instrument. In my model, where scale economies are allowed, non-concavity may also be driven by positive economies of scale (or counteracted by diseconomies of scale). If this is the case, the quota instrument is preferred by default. The derived rule is relevant for comparing the social welfare of instruments in situations where the marginal profit function is convex in harvest so that both instruments are effective.

The implications of the rule are consistent with the pro fee result under ecological uncertainty that Weitzman (2002) derives assuming no economies of scale. However, the rule I derive implies that a pro quota result may apply under ecological uncertainty if there are substantial diseconomies of scale in harvesting. This has not been shown before. For variable economic uncertainty, the rule is consistent with the simulation results of Hannesson and Kennedy (2005), since it implies that a pro quota result may apply under variable economic uncertainty. However, I show that for this to happen, the resource growth function must be highly concave locally around the optimum, otherwise fees are preferred. Finally, the rule implies that if structural economic uncertainty dominates, then the quota instrument is *always* preferred. This result and the investigation of structural economic uncertainty are also new. These new results showing that quotas are preferred in situations that may often apply qualify the pro fee message from prior studies.

The paper is organized as follows: In section 2, I develop the model of renewable resource harvesting, while in section 3, I set the stage for deriving the main result. In section 4, the instrument choice rule is derived and in section 5 implications are developed. Section 6 concludes the paper.

2. The Model

In this section, I develop a model of a renewable natural resource harvested by a ‘large’ number of firms. I use a discrete dynamic stock-recruitment model in which resource growth and harvest happen in distinct alternating time periods. This allows a detailed and explicit representation of ecological uncertainty, variable economic uncertainty and structural economic uncertainty as well as the stocks dynamics over time that tie them together. I end up using second order quadratic approximations of the key functions and, for transparency, I introduce the needed linearity and separability assumptions as the model is developed.

Let R_t, denote the resource stock available at the beginning of harvesting season t which I call 'initial stock' in the following. Let S_t denote the stock available at the end of the season *after* harvesters have completed the season's harvesting. Letting H_t, denote the industries aggregate harvest during season t. I assume that harvesting is the only factor which affects the resource stock during the harvesting season so that:

$$S_t = R_t - H_t \tag{1}$$

Corresponding to this, I assume that natural growth of the resource only takes place between seasons. I let the resource stock available at the beginning of season t be a function of the stock at the end of the previous harvesting season (S_{t-1}), as well as a stochastic variable (ε_t) which captures variations in resource growth due to climate etc:

$$R_t = F(S_{t-1}) + \varepsilon_t \tag{2}$$

I assume that $dR_t / dS_{t-1} \geq 0$, $d^2 R_t / d^2 S_{t-1} \leq 0$ and define $\bar{R}_t = F(S_{t-1})$ and so $\bar{R}_t = E\left[R_t\right]$.

The resource growth function (also called the stock-recruitment relation) allows harvestable growth of the natural resource to depend on the current resource stock. This is generally the case for forest and live stocks (fish, game), since growth may be constrained by parenting capacity when stocks are small, while competition for food and other resources may constrain growth when stocks are large. For resources such as water, leakage from lakes and ground water reservoirs typically increases with the water level and so also with the current 'stock' of water in the reservoir. Thus, even though gross inflow (from rain fall and streams) may not depend on the size of the reservoir, stock growth will, if leakage depends on the size of the reservoir.

The stochastic variable ε_t captures other exogenous effects on resource growth. For live stock, this could be variations in climate or the size of other live stocks which compete for the same resources, while for water resources this could be climate variations which affect precipitation. In the following, the regulator has to specify harvesting regulations prior to observing the realisation ε_t and so he can only base these regulations on his prior distribution over initial stock. Harvesters, on the other hand, experience the effect of stocks on their marginal profit as they harvest and so in effect observe the realisation. Thus, the ε_t stochastic variables capture, what in the introduction and in the literature in general, is called *ecological uncertainty*. The restrictive approximation that I make in (2) is that ε_t is additively separable from $\overline{R}_t$. As noted above, I need this to obtain manageable second order approximations of the core functions.

Turning now to the harvesting industry, let π denote the marginal profit of harvest for the representative harvester at any moment in time during harvesting season *t*. Let *x* denote the current resource stock at this particular moment in time, *h* denotes the accumulated harvest from the start of harvesting season *t* up to this moment in time. In order to get second order approximations of the core functions in the following, I assume that marginal profit is a linear function of current stock and accumulated catch i.e:

$$\pi = \theta\overline{\pi} \quad \text{where } \overline{\pi} = \tilde{b}x + kh + a\lambda_t \tag{3}$$

At the beginning of the harvesting season, the resource stock is equal to initial stock ($x = R_t$). However, as harvest progresses, stock is reduced by one unit for every unit harvested and so marginal profit is reduced by $\tilde{b}$ for every unit the current stock falls over the season. This captures the fact that the cost of harvesting resources (livestock, forest, water) typically depends on the size of the resource stock because of search and or extraction costs (see e.g. Neher (1990)). Livestock such as fish and game have to be localized before harvest and this becomes increasingly difficult as stock size falls. As forest is cleared, cutting must be undertaken in less accessible and more difficult areas. In much the same way, a low ground water table could mean that nearby wells run dry and that water must be transported from more distant deeper wells. In both cases, extraction costs increase as resource stocks are depleted, which implies that the marginal profit of harvesting depends on the current resource stock. The natural assumption here is that:

$$\tilde{b} \geq 0 \tag{4}$$

with equality applying when marginal profit does not depend on the size of the resource stock.

The parameter *k* captures economies of scale in harvesting that may characterize the harvesting technology. Thus, marginal profit increases by *k* for every unit harvested over the season because of these economies of scale (a negative *k* implies diseconomies of scale and if *k=0* there are no economies of scale). Economies of scale may result as capacity utilization of harvesting equipment increases. Diseconomies of scale may result if harvesting equipment breaks down more often as harvest levels come close to capacity.

The parameter *a<0* is a constant element of marginal profit and λ_t is a factor which captures the fact that marginal profit of harvesting may vary between harvesting seasons. I call this *variable economic uncertainty* which reflects the effect of changing climate and general economic conditions on marginal harvesting profit (for example bad weather or rising input costs may increase the costs of harvesting a given stock of fish or wild life during a given harvesting season, while changing output prices in the same way would affect marginal income from harvest). Thus, λ_t are stochastic variables ($E[\lambda_t]=1$) assumed to be independently distributed. I again ignore the second order effects that this type of uncertainty could have (e.g. on *b* or *k*) in order to obtain manageable approximations of the core functions in the following. The regulator does not observe the realisation of λ_t prior to specifying harvesting regulations for this season and so he can only base these regulations on his prior distribution over the profit function. Harvesters, on the other hand, experience the effect of weather and prices on marginal profit as they harvest and trade during the season and so in effect observe the realisation of λ_t. Clearly, variable economic uncertainty may be correlated with the regulator's ecological uncertainty (ε_t). For example, bad weather may increase the costs of harvesting a fish stock and at the same time this may also affect natural resource growth, thus causing variation over time in ε_t and λ_t to be correlated.

In addition to being uncertain about future weather and price conditions which affect marginal profit, the regulator may be uncertain about the size of the core parameters of the technology ($\tilde{b}, k, a$). Though harvesters can be assumed to know these parameters, regulators must estimate them using different kinds of information and they may in some cases be quite uncertain of these estimates. This is what I call *structural economic uncertainty*. The scaling parameter θ which characterizes the harvesting technology captures this. Thus, $\theta=1$ is the true profit function which characterizes harvesters and I assume that harvesters are aware of this. However, the regulator may attach positive probability to other θ values because of his uncertainty, but I assume that his estimate is unbiased (i.e. $E[\theta]=1$). Capturing regulator uncertainty about the basic harvesting technology in this way can be seen as a first order approximation of this type of uncertainty which ignores the fact that the regulator might be more uncertain about some of these parameters than about others. I ignore such second order effects in order to obtain manageable approximations of the core functions in the following.

Thus, the stochastic variables $\lambda_t, \lambda_{t+1}, ...$ and θ respectively capture different types of 'economic uncertainty'. On the one hand, $\lambda_t, \lambda_{t+1}, ...$ reflect the real economic and natural shifts in marginal profit of harvesting that have been the main focus of prior literature. Most other papers use the general term 'economic uncertainty' as being synonymous with this type of uncertainty. On the other hand, θ reflects basic uncertainty that the regulator has about the industry profit function parameters he must estimate. This type of uncertainty (I call it *structural economic uncertainty*) has not been studied before in this context. .

Clearly $h = R_t - x$ so defining $b = \tilde{b} - k$ I can restate marginal profit as:

$$\pi(x, R_t, \lambda_t, \theta) = \theta\overline{\pi}(x, R_t, \lambda_t, \theta) = \theta(bx + kR_t + a\lambda_t) \tag{5}$$

Thus, the parameter *b* aggregates the direct dependence of the marginal cost on current resource stock with the indirect dependence here on through economies of scale in harvesting.

The total profit of harvesting H_t during the season ($\Pi(H_t, R_t, \lambda_t, \theta)$) is found by integrating marginal profit from initial stock available at the beginning of the period (R_t) to the stock available at the end of the period (R_t-H_t):

$$\Pi(H_t, R_t, \lambda_t, \theta) = \int_{R_t - H_t}^{R_t} \pi(x, R_t, \lambda_t, \theta)dx \tag{6}$$

Given the assumed linear marginal profit function, total season profit $\Pi(H_t, R_t, \lambda_t)$ becomes a quadratic function (corresponding to a second order approximation of the true profit function). Thus:

$$\Pi(H_t, R_t, \lambda_t, \theta) = \theta\overline{\Pi}(H_t, R_t, \lambda_t) =$$
$$\theta\left(½b(R_t)^2 + (kR_t + a\lambda_t)R_t - ½b(R_t - H_t)^2 - (kR_t + a\lambda_t)(R_t - H_t)\right) \quad (7)$$
$$= \theta\left((b+k)H_tR_t - ½bH_t^2 + a\lambda_t H_t\right)$$

Regulation and the distribution and timing of information

I ignore issues of enforcement and compliance and assume that regulations are perfectly enforced. I also assume that quotas are tradable so that individual harvesters perceive and are constrained by the ITQ market price. Because of the fixed aggregate quota supply set by the regulator, the ITQ-price adjusts to ensure that the representative harvester complies with the aggregate quota. Thus there are no allocation differences between the two instruments, since aggregate harvest is allocated efficiently among harvesters under both regulatory instruments. There will only be a welfare difference between the two instruments if they result in different levels of aggregate harvest. This allows us to simplify by analyzing the effects for a single representative harvester.

At the beginning of each harvesting season, the regulator chooses between two regulatory instruments, a harvest fee, Φ_t, that the representative harvester must pay per unit harvested, or an aggregate harvest quota, Q_t, that the representative harvester must respect. The regulator may adjust the value of the chosen instrument at the beginning of each period. At the time when instrument values are set, the regulator observes the resource stock, S_{t-1}, but only knows a probability distribution over possible values of ε_t. Furthermore, the regulator knows the parameters a and b of the marginal profit function, $\pi(.)$, but only holds probability distributions over possible values of λ_t and θ. Thus, at the beginning of the harvesting season when the regulator sets the value of the chosen regulatory instrument (Φ_t or Q_t), the regulator's observation of the representative harvester's profit function and the available initial stock for the following season may be subject to uncertainty about ε_t, λ_t and θ. Harvesters, on the other hand, know θ and observe λ_t and current fish stock (in the sense that they observe prices and the realized relationship between effort and catch during the fishing season). Thus, the representative harvester in effect observes initial stock and his profit function with certainty. Given the value of the regulatory instrument set by the regulator at the beginning of the period, the harvester chooses the catch level that maximizes his profit (given $\theta = 1$ and the realisation of both ε_t and λ_t). Under quota regulation (assuming that the quota is binding), the harvester's catch as a function of the quota instrument value is simply:

$$H_t^Q(Q_t) = Q_t \tag{8}$$

The resulting period t total profit is $\Pi(H_t^Q, R_t, \lambda_t, \theta)$. The profit expected by the regulator at the beginning of period t is the expectation of this taken over ε_t and λ_t, θ ($E_t\left[\Pi(H_t^Q, R_t, \lambda_t, \theta)\right]$) where initial stock R_t defined in (1) depends on ε_t. Thus, the effect of the chosen instrument value on harvest can be predicted with certainty (assuming perfect compliance is obtained) by the regulator, but the resulting profit depends on ε_t and λ_t about which the regulator is uncertain.

Under fee regulation, the harvester chooses the harvest that maximizes profit, i.e.

$$\underset{H_t}{Max}\left(\int_{R_t - H_t}^{R_t} \pi(x, R_t, \lambda_t, \theta)dx - \Phi_t H_t \right) \tag{9}$$

The first order condition is:

$$\pi(R_t - H_t, R_t, \lambda_t, \theta) - \Phi_t = 0 \tag{10}$$

From equation (5) above:

$$\Phi_t = \theta\left(b(R_t - H_t) + kR_t + a\lambda_t\right) \tag{11}$$

Using (2) this implies that:

$$H_t^\Phi(\Phi_t) = (1 + k/b)\overline{R}_t + \varepsilon_t + (a\lambda_t - \Phi_t/\theta)/b \tag{12}$$

Thus, both the resulting harvest and aggregate fishing season profit depend on ε_t and λ about which the regulator is uncertain.

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3. Optimal Regulation

The regulator's problem at the beginning of period 1 is to maximize the sum of discounted expected future profit:

$$V(S_{t-1}) = \mathbf{E}_{\theta,t}\left[\theta\sum_{\tau=t}^{\infty}\alpha^{\tau-1}\overline{\Pi}(H_\tau, R_\tau, \lambda_\tau)\right] \tag{13}$$

where α is the discount factor and we remember that $R_\tau = \overline{R}_\tau(S_{\tau-1}) + \varepsilon_\tau$ and so depends on $S_{\tau-1}$ and ε_τ. Equation (13) is maximized subject to (1) and (6) conditional on the information available to the regulator at the beginning of period *t*. At this point in time, the regulator can observe S_t but not θ or the realizations of ε_t, λ_t (nor those in future periods) and so bases his solution on his prior distributions of these variables. Thus, expectations are taken over θ and stochastic variables in period *t* and all future periods. I use the bold expectation operator $\mathbf{E}_{\theta.t}$ to indicate that expectations are taken over stochastic variables in period t and all future periods (as well as over θ), while the normal expectation operator $E_{\theta.t}$ indicates that expectations are taken over stochastic variables *only* in period t (as well as over θ). The regulator's control variables are his choice of instrument and corresponding instrument value for each period. Let $H_\tau^I = H^I(i_\tau)$ denote the resulting harvest in period τ when the regulator chooses instrument I and sets the chosen instrument value to i_τ for period τ (i.e. under quota regulation the harvest-instrument function is given by (8) and under fee regulation by (12)). Let H_τ^* denote the harvest induced by optimal instrument choice and the optimal value of this instrument in period *t*. The optimal harvest in period τ is conditional on S_τ and on $\varepsilon_\tau, \varepsilon_{\tau+1} \ldots., \lambda_\tau, \lambda_{\tau+1}, \ldots, \theta$ and $H_{\tau+1}^*, H_{\tau+2}^* \ldots.$ so is also a stochastic variable over which the regulator only holds a distribution. Let $V^*(S_t)$ denote the discounted expected future profit when the regulator's policy is to implement optimal instrument choice and values in all future periods so that:

$$V^*(S_{t-1}) = \mathbf{E}_{\theta,t}\left[\theta\sum_{\tau=t}^{\infty}\alpha^{\tau-1}\overline{\Pi}(H_\tau^*, R_\tau, \lambda_\tau)\right] \tag{14}$$

Corresponding to (13) and (14), the recursive formulation (the Bellman equation) of the dynamic optimization problem becomes[7]:

$$V^*(S_{t-1}) = \underset{I_t, i_t}{Max} W^*(S_{t-1}) \tag{15}$$

Where:

$$W^*(S_{t-1}) = E_{\theta,t}\left[\theta\overline{\Pi}(H_t^I, R_t, \lambda_t)\right] + \alpha E_{\theta,t}\left[V^*(R_t - H_t^I)\right] \tag{16}$$

The value function, $V^*(S_{t-1})$, is the expected sum (taken over $\varepsilon_t, \varepsilon_{t+1} \ldots, \lambda_t, \lambda_{t+1}...., \theta$,) of discounted future profit under the optimal policy, conditional on S_{t-1}. $V^*(R_t - H_t^I)$ is the corresponding expectation (taken over $\varepsilon_{t+1}, \varepsilon_{t+2} \ldots,\ \lambda_{t+1}, \lambda_{t+2}...., \theta$. Since S_t is observed at the start of period *t+1* and so the explicit expectation in (13) is taken only over θ and stochastic variables in period *t* (as indicated by the expectation operator $E_{\theta,t}$). Thus, the problem formulated in (15) is that of finding the optimal instrument and instrument value in period 1, conditional on optimal instruments and values being implemented in all future periods.

By assuming a linear marginal profit function, I have assumed the second order quadratic (Taylor) approximation of the current period profit function. To arrive at linear marginal cost and benefit curves, I must do the same for the value function for aggregated discounted future profit under optimal policy, i.e:

$$\begin{aligned}&\alpha V^*(R_t - H_t^I) = \alpha \mathbf{E}_{\theta,t+1}\left[\theta \sum_{\tau=t+1}^{\infty} \alpha^{t-1}\overline{\Pi}(H_\tau^*, R_\tau, \lambda_\tau)\right] = \\ &\alpha \mathbf{E}_{\theta,t+1}\left[\theta\left(\mathbf{c}(R_t - H_t^I) - ½\mathbf{d}(R_t - H_t^I)^2 - \mathbf{g}(\theta)\right)\right]\end{aligned} \tag{17}$$

We could increase the precision of the approximation by including higher order elements. However, to keep things manageable, I assume that a second order Taylor approximation of the mean value function is sufficiently accurate within the relevant span of variable variation. Note that variation in θ may affect the mean value function because catch implemented by the regulator's policy may be affected by θ . This is the case if the regulator uses the fee instrument, since the profit maximizing

[7] The recursive form is found by inserting the definitions $V^*(S_t) = \mathbf{E}_{\theta,t+1}\left[\theta \sum_{\tau=t+1}^{\infty} \alpha^{\tau-1}\overline{\Pi}(H_\tau^*, R_\tau, \lambda_\tau)\right]$ and $S_{t+1} = R_t - H_t^I$ into (14) and formulating the underlying maximization problem in terms of current period decisions conditional on optimal future period decisions (see, e.g. Ljungqvist and Sargent (2000)).

catch chosen by resource harvesters given the fee will depend on this parameter. Any effect of θ on the mean value is approximated by the g(.) function and I have here assumed that interactions between θ and $R_t - H_t^I$ are small enough that they can be ignored. Thus, $\mathbf{c}$ and $\mathbf{d}$ depend on ε_{t+1}, $\varepsilon_{t+2}\ldots$, $\lambda_{t+1}, \lambda_{t+2}$......but our approximation implies that they do *not* depend on the θ parameter. From this function, I now derive the linear curve which describes foregone marginal future profit when harvesting in the current period and the linear curve for current marginal profit of harvest. It is from these two linearized curves that I will derive the core results.

Inserting the approximation (17), and the definition $S_1 = R_1 - H_t^I$ into (16) we have the recursive formulation:

$$W^*(S_t) = E_{\theta,t}\left[\theta\overline{\Pi}(H_t^I, R_t, \lambda_t)\right] + E_{\theta,t}\left[\mathbf{E}_{\theta.t+1}\left[\theta\mathbf{c}(R_1 - H_1^I) - \theta ½\mathbf{d}(R_1 - H_1^I)^2 - \mathbf{g}(\theta)\right]\right] \quad (18)$$

It is important that S_1 only depends on ε_1 and λ_1 since ε_1 and λ_1 are independent of future period stochastic variables so that S_1 does not co-vary with $\mathbf{c}$ or $\mathbf{d}$. Because of the independence of stochastic variables between periods, this can be written:

$$W^*(S_t) = E_{\theta,t}\left[\theta\overline{\Pi}(H_t^I, R_t, \lambda_t)\right] + E_{\theta,t}\left[\theta(c(R_t - H_t^I) - ½d(R_t - H_t^I)^2) + g(\theta)\right] \quad (19)$$

where $g(\theta) = \mathbf{E}_{t+1}\left[\mathbf{g}(\theta)\right]$ $c = \mathbf{E}_{t+1}\left[\mathbf{c}\right]$ and $d = \mathbf{E}_{t+1}\left[\mathbf{d}\right]$. Inserting (7) and regrouping we have:

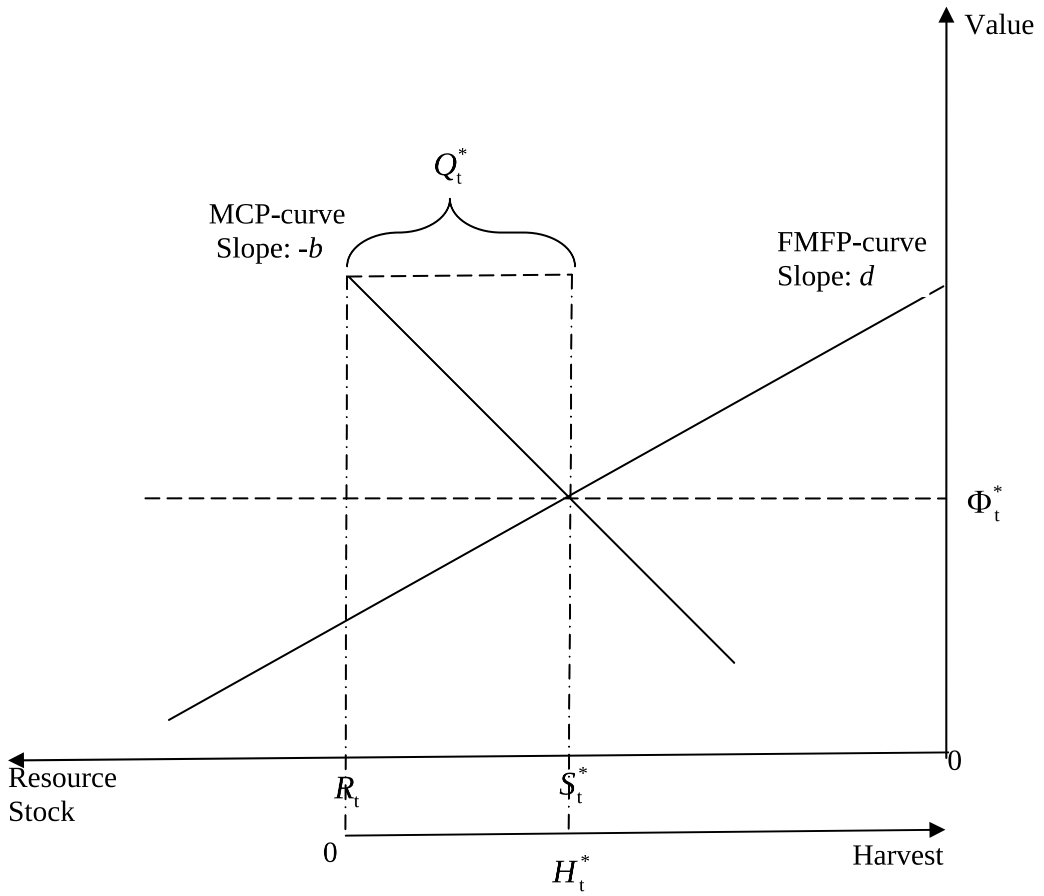
$$W^*(S_t) = E_{\theta,t}\left[\theta\left((b+k)H_t R_t - ½bH_t^2 + a\lambda_t H_t\right)\right] + E_{\theta,t}\left[\theta(c(R_t - H_t^I) - ½d(R_t - H_t^I)^2) + g(\theta)\right] \quad (20)$$

The first order condition for maximizing expected profit in (17) using the policy instrument H_t^I is:

$$\frac{dW^*(S_t)}{dH_t^I} = E_{\theta,t}\left[\theta\left(b(R_t - H_t^I) + kR_t + a\lambda_t\right)\right] + E_{\theta,t}\left[\theta\left(d(R_t - H_t^I) - c\right)\right] = 0 \quad (21)$$

This is the key equation which captures the regulator's problem of allocating the current resource stock between the benefits of current harvest and the benefits of leaving stock for future growth and harvest. Figure 1 illustrates this graphically. In the diagram, we have value in monetary units on the y-axis and current resource stock increasing as we move left on the x-axis. Thus, the resource stock available at the beginning of the harvest season R_t is reduced through harvest during the season moving the stock to the right along the x-axis leaving a stock of S_t at the end of the season. The extra x-axes below the figure thus measures current harvest as one moves to the right (with harvest increasing from 0 as stock is reduced from R_t at the beginning of the season).

Figure1. *Costs and benefits of harvest*



The first element of (21) is expected Current Marginal Profit of harvesting, which is depicted as the downward sloping MCP-curve in figure 1 with the equation:

$$MCP = E_{\theta,t}\left[\theta\left(a\lambda_t + (b+k)R_t - bH_t^I\right)\right] = \left(a + (b+k)\bar{R}_t\right) - b\bar{H}_t^I \tag{22}$$

The parenthesis $\left(a + (b+k)\bar{R}_t\right)$ is expected marginal profit of the first unit harvested during the season, where resource stock is equal to expected initial stock $\bar{R}_t$. The parameter *b* is the reduction in marginal profit of harvesting when the resource stock is reduced by one unit through harvest and so the slope of the current marginal profit curve is *–b*. Though I have depicted a downward sloping curve, this may not always be the case. If economies of scale are sufficiently large relative to the marginal cost effect of resource stocks (so that $k > \tilde{b} > 0$), then *b* would be negative and the curve would be upward sloping. In this case, unregulated harvest would wipe out the resource during the first season because the profit function would be convex.

The second element of (21) is expected Foregone Marginal Future Profit of harvesting now, i.e. the reduction in future profit when one less unit of resource stock is left to reproduce and be harvested in the future. This is depicted by the upward sloping FMFP-curve in figure 1 with the equation:

$$FMFP = E_{\theta,t}\left[\theta\left(c - dR_t + dH_t^I\right)\right] = \left(c - d\bar{R}_t\right) + d\bar{H}_t^I \tag{23}$$

The parenthesis $\left(c - d\bar{R}_t\right)$ is expected foregone marginal future profit of the first unit harvested during the season where resource stock is equal to expected initial stock $\bar{R}_t$. The parameter *d* is the reduction in expected marginal future profit when the resource stock left for the future is decreased by one unit through current harvest. Therefore, the slope of the curve of expected foregone marginal future profit as a function of current catch is *d*. I have depicted this curve as upward sloping which implies that $d > 0$. This is not necessarily so as we will see below. However, irrespective of the sign of *d*, I assume that:

$$d > -b \tag{24}$$

If this were not the case, it would be efficient to harvest the whole resource stock in the first period and leave nothing for future harvest. In this situation, there would be no reason for regulating harvesters at all. Thus, the analyses we are undertaking are only relevant if the assumption holds.

The regulator wants to induce a current level of catch that ensures equality of marginal current profit and forgone expected marginal future profit at the *end* of the harvesting season (where the two curves cross) so that the optimal stock S_t^* is left for the future. If there is no uncertainty, the regulator could calculate S_t^* and the corresponding optimal catch H_t^* exactly and set either a fee or a harvest quota that implements this with certainty. The regulator's problem is that he is uncertain about θ, λ_t and ε_t (and so about $R_t = \bar{R}_t + \varepsilon_t$). These parameters affect the location of both curves and thereby the location of optimal catch and the catch implemented by setting a fee or a quota.

4. The Decision Rule for Instrument Choice

In this section, I first find the optimal values of each of the two instruments. I then calculate the expected welfare under optimal regulation using each of the two instruments and derive a general rule for when one instrument should be preferred to the other and how this depends on the different kinds of uncertainty that we have specified. I then conclude the section by investigating the implications of this decision rule in detail.

Optimal fee and quota regulation

First I find the values of each of the two instruments that maximize expected welfare conditional on the given instrument being used in the current period.

Rearranging (21), we see that to maximize expected welfare, the chosen instrument in period *t* must be set so that:

$$E\left[H_t^{I*}\right] = E_t\left[(1+k/(b+d))R_t + \frac{(a\lambda_t - c)}{(b+d)}\right] = (1+k/(b+d))\bar{R}_t + \frac{(a-c)}{(b+d)} \qquad (25)$$

This implies that if the quota instrument is used, the optimal quota (Q_t^*) is:

$$Q_t^* = (1+k/(b+d))\bar{R}_t + \frac{(a-c)}{(b+\bar{d})} \qquad (26)$$

and the realized catch with optimal management using this instrument becomes:

$$H_t^{Q*} = Q_t^* \tag{27}$$

Now consider the fee instrument. From (12) we have that $H_t^{\Phi*}(\Phi_t^*) = (1 + k/b)\bar{R}_t + \varepsilon_t + (a\lambda_t - \Phi_t^*/\theta)/b$ so that taking expectations we have $E_t\left[H_t^{\Phi*}(\Phi_t^*, \lambda_t, R_t)\right] = (1 + k/b)\bar{R}_t + (a - \Phi_t^*)/b$ implying that:

$$H_t^{\Phi*}(\Phi_t^*, \lambda_t, R_t) - E_t\left[H_t^{\Phi*}(\Phi_t^*, \lambda_t, R_t)\right] = \varepsilon_t + (\lambda_t - 1)a/b + (1 - 1/\theta)\Phi_t^*/b \tag{28}$$

The fee must be set so that (25) is satisfied, i.e. so that:

$$E_t\left[H_t^{\Phi*}(\Phi_t^*, \lambda_t, R_t)\right] = (1 + k/(b+d))\bar{R}_t + \frac{(a-c)}{(b+\bar{d})} \tag{29}$$

Thus, inserting (26) and (29) in (28), realized catch under the optimal fee becomes:

$$H_t^{\Phi*}(\Phi_t^*, \lambda_t, R_t) = Q_t^* + \varepsilon_t + \tilde{\lambda}_t - \tilde{\theta}$$

$$\text{where } \tilde{\theta} = (1/\theta - 1)\Phi_t^*/b \text{ and } \tilde{\lambda}_t = (\lambda_t - 1)a/b \tag{30}$$

We use these derived stochastic variables in the following for ease of presentation. Note that $E\left[\tilde{\theta}\right] \geq 0$ and $\mathrm{E}\left[\tilde{\lambda}_t\right] = 0$ follows directly from the underlying distributional assumptions.

Welfare under optimal fee and quota regulation

Now I compare the welfare of using the optimal fee regulation with using optimal quota regulation in period 1, assuming that the optimal instrument and the optimal value of this instrument is used in all the following periods. Let $V^{Q*}(S_0)$ denote the value of expected discounted profit (welfare) under optimal quota regulation in period 1, assuming optimal regulation in all following periods, and let $V^{\Phi*}(S_0)$ denote welfare when optimal fee regulation is used in period 1. Note that if quota regulation in period 1 is superior to fee regulation, $V^*(S_0) = V^{Q*}(S_0) > V^{\Phi*}(S_0)$ while $V^*(S_0) = V^{\Phi*}(S_0) > V^{Q*}(S_0)$ if the opposite is the case. Inserting (26) into (20), expected welfare, if quota regulation is chosen for the current period and the optimal instrument is chosen in all future periods, becomes:

$$V^{Q*}(S_0) = E_1\left[\theta\begin{pmatrix} -½(b+d)(R_1 - Q_1^*)^2 + kQ_1^*R_1 \\ -(a\lambda_1 - c)(R_1 - Q_1^*) + ½b(R_1)^2 + a\lambda_1 R_1 \end{pmatrix} + g(\theta)\right] \tag{31}$$

For fee regulation in the first period and regulation by the optimal instrument in all following periods we find expected welfare by inserting (30) into (20):

$$V^{\Phi *} = E_1\left[\theta\begin{pmatrix} -½(b+d)(R_1 - Q_1^* - \varepsilon_1 - \tilde{\lambda}_1 + \tilde{\theta})^2 + k(Q_1^* + \varepsilon_1 + \tilde{\lambda}_1 - \tilde{\theta})R_1 \\ -(a\lambda_1 - c)(R_1 - Q_1^* - \varepsilon_1 - \tilde{\lambda}_1 + \tilde{\theta}) + ½b(R_1)^2 + a\lambda_1 R_1 \end{pmatrix} + g(\theta)\right] \qquad (32)$$

Rearranging terms we have:

$$\begin{aligned} V^{\Phi *} &= E_1\left[\theta\begin{pmatrix} (b+d)(R_t - Q_t^*)(\varepsilon_t + \tilde{\lambda}_1 - \tilde{\theta}) - ½(b+d)(\varepsilon_t + \tilde{\lambda}_1 - \tilde{\theta})^2 \\ +k(\varepsilon_t + \tilde{\lambda}_1 - \tilde{\theta})R_1 + (a\lambda_t - c)(\varepsilon_t + \tilde{\lambda}_1 - \tilde{\theta}) \end{pmatrix}\right] \\ &+ E_1\left[\theta\begin{pmatrix} -½(b+d)(R_1 - Q_1^*)^2 + kQ_1^* R_1 \\ -(a\lambda_t - c)(R_1 - Q_1^*) + ½b(R_1)^2 + a\lambda_1 R_1 \end{pmatrix} + g(\theta)\right] \end{aligned} \qquad (33)$$

So that using (31) we have:

$$V^{\Phi *} = E_1\left[\theta\begin{pmatrix} (b+d)(R_1 - Q_1^*)(\varepsilon_1 + \tilde{\lambda}_1 - \tilde{\theta}) - ½(b+d)(\varepsilon_1 + \tilde{\lambda}_1 - \tilde{\theta})^2 \\ +k(\varepsilon_1 + \tilde{\lambda}_1 - \tilde{\theta})R_1 + (a\lambda_1 - c)(\varepsilon_1 + \tilde{\lambda}_1 - \tilde{\theta}) \end{pmatrix}\right] + V^{Q*}(S_0) \qquad (34)$$

This is useful since this equation directly implies the conditions for expected welfare with one instrument being greater than the other. As θ is not correlated with λ_1 or ε_1 this reduces to (see appendix A for details):

$$V^{\Phi *} = \begin{pmatrix} ½(b+d+2k)E\left[\varepsilon_t \varepsilon_t\right] \\ +½(b-d)E\left[\tilde{\lambda}_t \tilde{\lambda}_t\right] + (b+k)E\left[\varepsilon_t \tilde{\lambda}_t\right] \\ -½(b+d)E\left[\tilde{\theta}\right](\Phi_t^* / b) \end{pmatrix} + V^{Q*} \qquad (35)$$

where $\tilde{\theta} = (1 - 1/\theta)\Phi_t^* / b$ and $\tilde{\lambda}_t = (\lambda_t - 1)a / b$

The equation shows how the expected welfare difference between the two instruments depends on the regulator's ecological uncertainty ($E\left[\varepsilon_t \varepsilon_t\right] > 0$), the regulator's variable economic uncertainty ($E\left[\tilde{\lambda}_t \tilde{\lambda}_t\right] > 0$) and the regulator's structural economic uncertainty ($E\left[\tilde{\theta}\right](\Phi_t^* / b)$). Note that the term ($E\left[\tilde{\lambda}_t \varepsilon_t\right]$) is a standard correlation term that readjusts the basic ecological and variable economic uncertainty effects for any correlation between them. In the next section, we study the implications of the choice rule in detail.

5. Implications of the Instrument Choice Rule

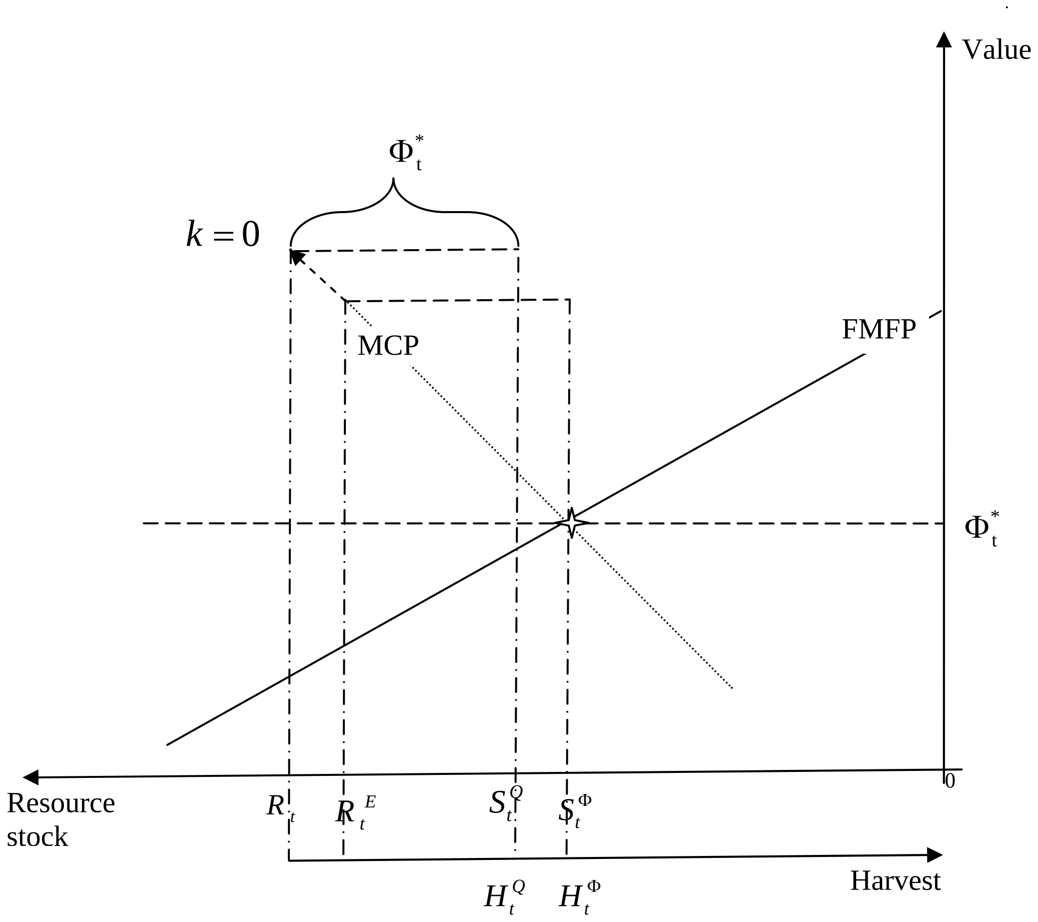
The size and sign of effects of the three types of regulator uncertainty on optimal instrument choice depend on three key parameters: marginal current profit of harvesting at the end of the season (*b*), expected marginal future profit of leaving this unit for future harvest (*d*), and the economies of scale in harvesting (*k*). I investigate how in the following subsections.

Clearly, fees become ineffective as a regulatory instrument if marginal profit is not strictly concave in harvest. If harvesters, with a convex profit function, face a fee, they would find that one of the two corner solutions would maximize their profit and so they would either choose not to harvest at all, or to harvest until the resource was depleted. When this is the case, quota regulation is obviously preferred. When there are no economies of scale, this will happen if marginal profit does not depend on the resource stock (i.e. when $\tilde{b}$ =0 as, e.g. Hannesson and Kennedy (2005) have pointed out). However, economies of scale also influence convexity and the effectiveness of the fee instrument. If economies of scale (*k*) are positive and larger than the marginal cost effect of resource stocks (i.e. if $k > \tilde{b}$), then $b \leq 0$ and the profit function becomes convex in the resource stock and harvest. Thus, even when marginal profit depends on the resource stock, positive economies of scale may render fees ineffective. On the other hand, even if marginal profit does not depend on the resource stock, diseconomies of scale can ensure the effectiveness of the fee instrument. If there are economies of scale, it is the combined effect of scale economies and resource stock dependence that is important, i.e. when $b \leq 0$, a fee ceases to be an effective instrument for regulation and so quotas are preferred by default. The rule we have derived applies for concave marginal profit functions (when $b > 0$) and I will assume this when developing the implications of the rule below.

Ecological uncertainty

Let us first consider how ecological uncertainty ($E\left[\varepsilon_t\varepsilon_t\right]$>0) alone affects instrument choice assuming that there are no economies of scale (*k*=0). These are the assumptions made by Weitzman (2002) in his analysis of renewable resource regulation under ecological uncertainty. Remembering that –*d* < *b* and that when *k=0* we have $b = \tilde{b} > 0$ it is clear that the coefficient to this effect is always positive. Thus, ecological uncertainty *always* implies that the fee instrument should be preferred when there are *constant returns to scale* in resource harvesting. The intuition behind this is illustrated in figure 2 (which replicates figure 1). Here ecological uncertainty implies that the regulator is uncertain about where the current marginal profit curve starts at the beginning of the season. I illustrate this in figure 2 by letting actual initial stock (R_t) be larger than the initial stock expected by the regulator (R_t^E). Clearly this implies that the regulator also becomes uncertain about what end of season stock a given quota would imply. In our example, the regulator expecting initial stock R_t^E sets the quota expecting to implement S_t^* but instead implements end of season stock S_t^Q. However, even though the regulator is uncertain about initial stock, this does not affect the position of the current marginal profit curve as such (as long as there are no economies of scale). Thus, the regulator can still correctly predict the optimal stock at the end of the season (S_t^*), as well as the corresponding current marginal profit at this stock level. He can, therefore, ensure implementation of this stock level at the end of the season with certainty by setting the fee equal to this marginal profit level (Φ_t^*). This result, and the argument for it, corresponds to the result and argument presented in Weitzman (2002) and in fact when $k = 0, \lambda_t = 0, \theta = 0$ our model reduces to a second order approximation of the model that was developed and analyzed in that paper.

Figure 2 *Ecological uncertainty without economies of scale*

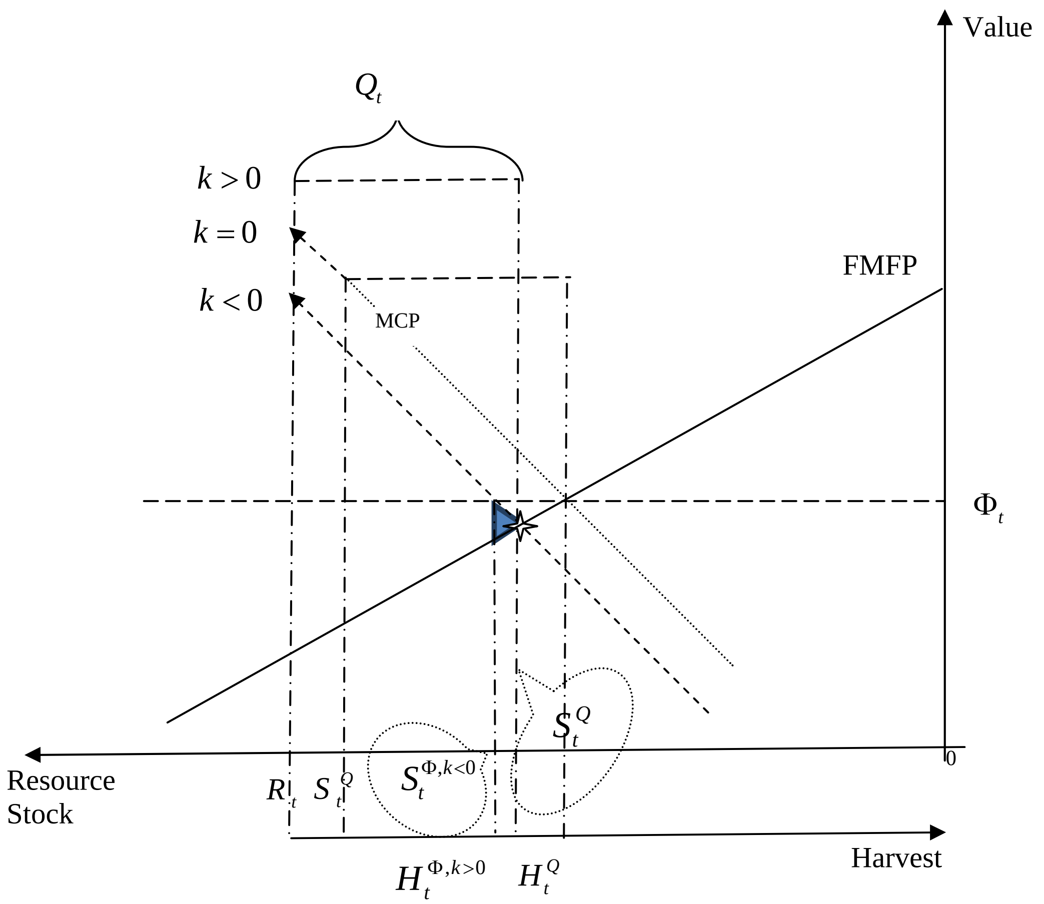


However, if we introduce economies of scale, Weitzman's clear pro fee result for ecological uncertainty breaks down. Formally we see this in (35) since if *k* is negative and so large numerically that $\tilde{b} < -k$ then the coefficient to $E[\varepsilon_t \varepsilon_t]$ becomes negative. A negative *k*, where $\tilde{b} < -k$, corresponds to diseconomies of harvesting scale that are larger per resource unit than the economies provided by the resource stock This is illustrated in figure 3. When $k \neq 0$ then uncertainty about R_t not only implies uncertainty about where the marginal current profit curve starts, but also shifts the curve itself. If there are diseconomies of scale, then an unexpectedly larger R_t also implies that marginal profit at R_t^E (and all other points on the curve) are lower than expected so that the marginal profit curve shifts down relative to the expected curve, as illustrated in figure 3 (the broken curve labelled *k<0*). The unexpected shift in end of season stock under quota regulation S_t^Q is the same as in figure 2, but the downward shift in the curve now implies that the optimal end of season stock (S_t^*) also shifts left and that the end of season stock implemented by the fee (S_t^Φ)

shifts even more to the left. If *k* is numerically small, these shifts are small and the fee will still be preferred. However, if *k<0* is sufficiently large numerically (implying a sufficiently large downward shift in the marginal current profit curve), then S_t^* shifts more to the right than S_t^Q which implies that the quota now results in an end of season stock which is closer to the optimal than the fee would (as illustrated in the figure). Thus, the fee has an advantage that is associated with the initial uncertainty about where the curve starts, but a disadvantage associated with the downward shift of the curve because of scale diseconomies. If this shift is large enough, this disadvantage will outweigh the initial advantage and a quota becomes the preferred instrument.

If economies of scale are positive, this increases the welfare advantage of fee regulation (as seen in (35). This situation implies an upward shift of the marginal current profit curve and it is easy to see that no matter how large the upward shift, the welfare loss associated with a quota will always be larger than the welfare loss associated with the fee. Thus, as long as *b>0* (i.e. as long as $k < \tilde{b}$), fees are preferred. As discussed above, if *b<0* then fees become ineffective as a regulatory instrument and quotas are preferred.

Figure 3 *Ecological uncertainty with diseconomies of scale*

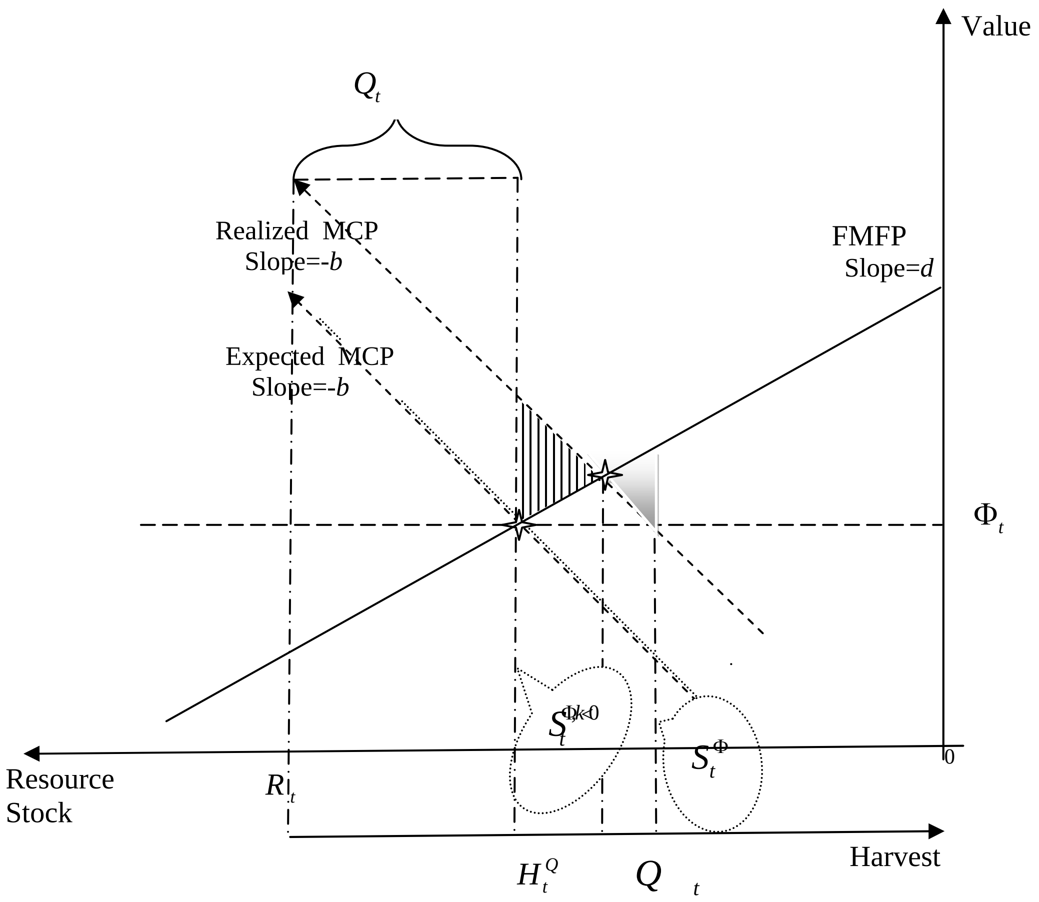


In conclusion, as long as economies of scale are numerically small relative to the marginal profit effect of resource stocks, Weitzman's clear pro fee result holds. However, diseconomies of scale that are numerically large enough compared to the marginal profit effect of resource stocks, imply that quota regulation should be preferred.

Variable Economic Uncertainty

Moving to the second element of equation (35), variable economic uncertainty ($E\left[\tilde{\lambda}_t\tilde{\lambda}_t\right]$>0), we see that the sign of the coefficient to this effect depends on the sum of the two curves' slope. If the current profit curve slopes down more than the forgone future profit curve slopes up, fees are preferred. If the opposite is the case, quotas should be preferred. The intuition behind this can be seen in figure 4. Variable economic uncertainty is an additive element in the MCP-curve and so this type of uncertainty causes an unexpected shift of the curve without changing the slope. Note that the illustrated slopes correspond to $b>d$ where the fee instrument should be preferred.

Figure 4. *Variable economic uncertainty*



In figure 4, both the expected and the realized curve are illustrated. The regulator sets the instrument he uses (Q_t and Φ_t) so that expected harvest and final stock are optimal (as illustrated by the left star indicating the intersection of the FMFP kurve and the expected MCP kurve.). This is precisely what the quota instrument implements (S_t^Q and H_t^Q), while the fee instrument implements a harvest and final stock that deviates from this (S_t^{Φ} and H_t^{Φ}). Of course optimal stock and harvest for the realized curve (S_t^* and H_t^*) also deviate and the question is which instrument results in the smallest welfare loss. It is easy to see that the welfare loss which results from quota regulation corresponds to the lined triangle, while the welfare loss that results from fee regulation corresponds to the smaller shaded triangle. In this case, the fee is preferred, corresponding to the illustrated relative slopes. It is also easy to see that the relative size of the two triangles is reversed if the relative slope size of the two curves' is reversed. .

This type of uncertainty and the resulting decision rule parallel the original Weitzman (1974) analysis. In that paper, Weitzman considers how uncertainty, which shifts what corresponds to our current profit curve, affects instrument choice and he finds that this decision rule applies. In fact, when $\varepsilon_{\mathrm{t}} = 0, \theta = 0$, our model reduces to a model that is formally equivalent to Weitzman's (1974). However, though formally equivalent, our underlying model differs from Weitsman's since in our case, both curves derive from the same profit function. I therefore investigate this dependence and what can be said about the decisive relationship between the two slopes *b* and *d.* We saw above that if *b* is close to or equal to zero, the fee becomes ineffective because of non-concavity and quotas are preferred. When this is not the case (i.e. when *b*>0), *d>0* must be larger than *b* for *(b-d)* to be negative.

To find *d* I evaluate the second derivative of $V^*(S_1)$ with respect to H_1 because, from the second order Taylor approximation (17), we know that:

$$d = -\alpha \frac{dV^2(S_1)}{d^2 S_1} \tag{36}$$

First note that the slope of the forgone marginal future profit curve in period one is conditional on optimal instrument choice and regulation in period 2 and so on. Now consider $V^*(S_1)$ where the definition (14) implies that the first derivative is:

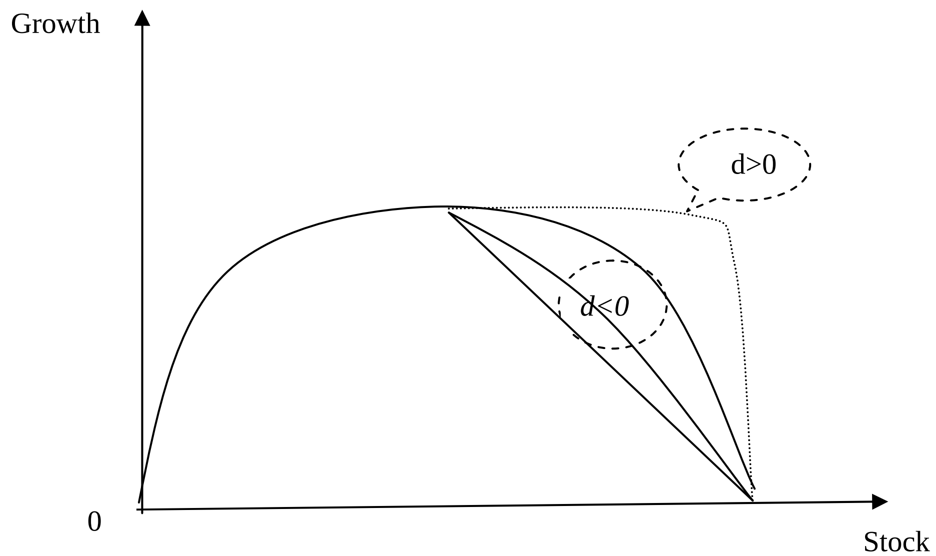
$$\begin{aligned}
&\frac{dV^*(S_t)}{dS_t} = \mathbf{E}_{\theta,t+1}\left[\theta \sum_{\tau=t+1}^{\infty} \alpha^{t-1} \frac{d\overline{\Pi}(H_\tau^*, R_\tau, \lambda_\tau)}{dR_\tau}\frac{dR_\tau}{dS_t}\right] \\
&\text{where } \mathbf{E}_{\theta,t+1}\left[\theta \frac{d\overline{\Pi}(H_\tau^*, R_\tau, \lambda_\tau)}{dR_\tau}\frac{dR_\tau}{dS_t}\right] = \\
&\mathbf{E}_{t+1}\left[\left(\underset{+}{\frac{\delta\overline{\Pi}(H_\tau^*, R_\tau, \lambda_\tau)}{\delta H_\tau^*}}\ \underset{+}{\frac{\delta H_\tau^*}{\delta R_\tau}} + \underset{+}{\frac{\delta\overline{\Pi}(H_\tau^*, R_\tau, \lambda_\tau)}{\delta R_\tau}}\right)\underset{+}{\frac{dR_\tau}{dS_t}}\right]
\end{aligned} \tag{37}$$

where the signs of the derivatives assumed above are indicated. Thus, the second derivative of $V^*(S_1)$ becomes:

$$\frac{d^2V^*(S_t)}{d^2S_t} = \mathbf{E}_{t+1}\left[\sum_{\tau=t+1}^{\infty}\alpha^{t-1}\left(\underset{+}{\frac{d^2\overline{\Pi}_\tau}{d^2R_\tau}}\underset{+}{\frac{dR_\tau}{dS_t}} + \underset{+}{\frac{d\overline{\Pi}_\tau}{dR_\tau}}\underset{\div}{\frac{d^2R_\tau}{d^2S_t}}\right)\right] \tag{38}$$

where the signs of the underlying derivatives are indicated. Thus, *d* will only be positive if the negative second derivative of the growth function is numerically large. If, for example, the growth function is characterized by a constant growth rate, the second derivative will be zero and then *d* will be negative, irrespective of the form of the profit function characterizing harvesters, implying that the fee instrument is preferred. The reason that the growth function's concavity is critical for a positive FMFP-curve slope is that marginal profit is always rising with initial stock. Thus, as the stock in period 2 increases, so does marginal profit which in itself implies a negative slope since marginal profit then falls with period 1 harvest. *d* will only be positive if the growth function is sufficiently concave around optimum. This requirement is quite restrictive. For example, the logistic growth function, which is common in renewable resource modelling, is not 'sufficiently' concave (see appendix B) and will generally imply a negative *d* slope (as illustrated in figure 5).

Figure 5. *Concavity of the growth function and the sign of d.*



Since b>0 for d>b the growth function must be *highly* concave around optimum. Concavity of the growth function implies that, as end of season stock increases, so does competition for food and ecological space, leakage from groundwater reservoirs, etc. so that marginal net growth which results from increasing end of season stock (the second derivative) falls. For the growth function to be highly concave, such effects must 'kick in' over a relatively short span of stock values.

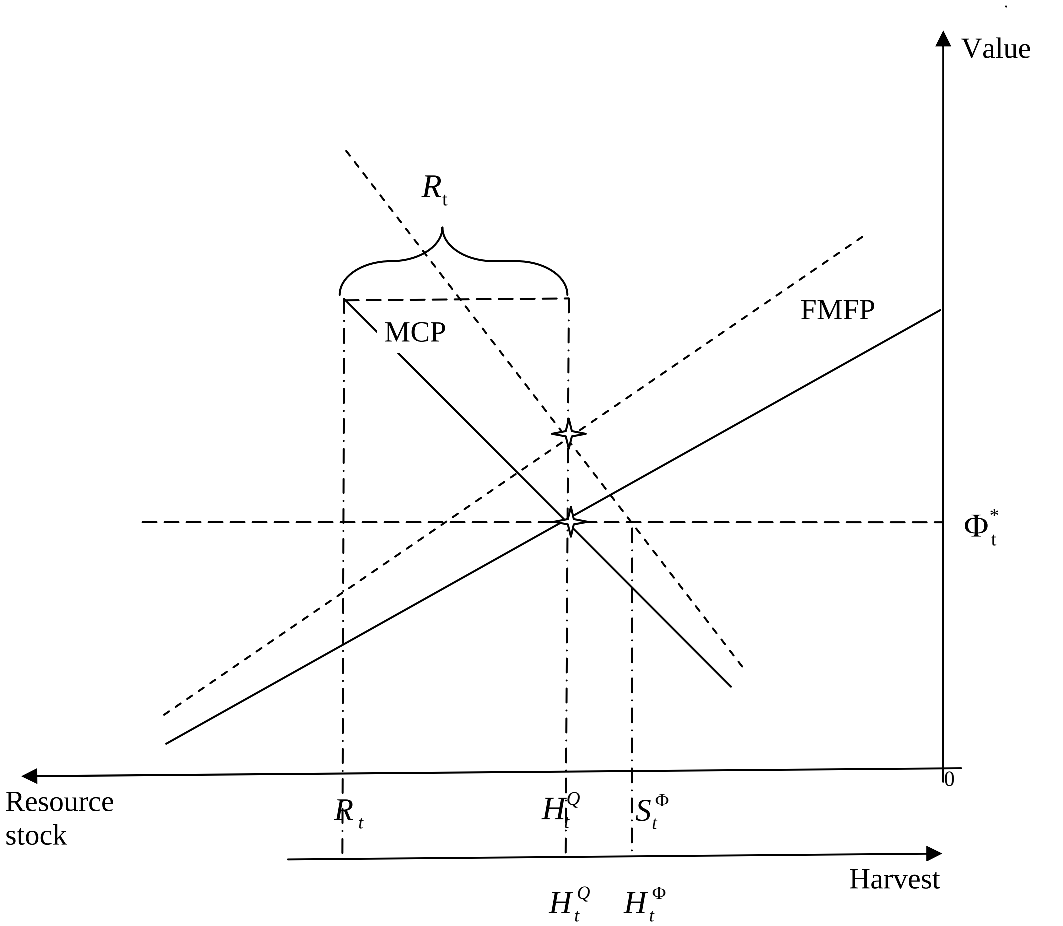
In conclusion, variable economic uncertainty generally implies that fees are the preferred instrument. Only if the growth function is highly concave around optimum can quotas become the preferred instrument.

Structural Economic uncertainty

The fourth element of equation (35) captures structural economic uncertainty ($E\left[\tilde{\theta}\right](\Phi_t^* / b)$). If $b \leq 0$ the fee instrument is ineffective and so quotas are preferred, as we saw above. When assuming $b > 0$ then $E\left[\tilde{\theta}\right](\Phi_t^* / b)$ >0. We see that the sign of the coefficient is always negative since by assumption d > –b so that the quota instrument is always preferred when this type of uncertainty dominates.

The intuition behind this is illustrated in figure 6.

Figure 6. *Structural economic uncertainty*



In figure 6, both the expected MCP- and FMFP-curves are illustrated by solid lines (expected R_t =1). The realised MCP- and FMFP-curves (here a value of R_t >1) are illustrated by broken lines. The important thing to realize (se equatios 21) is that θ factors multiplicatively on both curves so that any realisation of θ which differs from the expected one, results in the same proportional upward shift of both curves. This causes an upward shift in the optimal crossing point's marginal profit value, but preserves the value of the optimal final stock (as indicated). Thus, with no uncertainty about initial stock or about the optimal final stock, the quota instrument will always implement the optimum (S_t^Q and H_t^Q). This is clearly not the case for the fee instrument (S_t^Φ and H_t^Φ) since realized harvest depends on the location of the MCP-curves about which the regulator is uncertain. In conclusion, structural economic uncertainty in itself *always* implies that quotas are preferred.

6. Conclusion

I have derived a general rule for how instrument choice depends on three types of regulator uncertainty: ecological uncertainty, variable economic uncertainty and structural economic uncertainty. The rule is derived from a quite general dynamic model, but it is still relatively simple and easy to interpret. The main qualification is that I must apply second order approximations of the underlying functions and additive separability in order to do this. This means that I generally disregard second order effects. However, the approximation does capture the main effects in a structured way, and perhaps just as importantly, it is often not practically feasible for policy makers and regulators to estimate the key underlying functions with greater accuracy.

Quotas are preferred whenever marginal profit is not strictly concave in harvest since then fees are no longer an effective instrument for regulation. Non-concavity can result because of positive economies of scale and/or if there is little dependence of marginal profit on resource stock. In contrast diseconomies of scale will ensure concavity even when marginal profit does not depend on the resource stock. The decision rule developed above applies for industries with strictly concave marginal profit functions where both instruments are effective.

The rule implies that, when fees are an effective instrument of regulation, then:

- Fees are generally preferred if ecological uncertainty dominates, but a quota may be preferred if there are substantial diseconomies of scale in harvesting,
- Fees are generally preferred if variable economic uncertainty (e.g. uncertainty about output prices) dominates, but a pro quota result may apply if the growth function is highly concave around optimum.
- Finally, if structural economic uncertainty (about underlying profit function parameters) dominates, the quota instrument is *always* preferred.

These implications of the rule are consistent with prior results, but they also add to them. The fact that diseconomies of scale under ecological uncertainty favour quotas and that structural economic uncertainty favours quotas has not been shown previously.

However, the main contribution of this paper is to bring all these results into a simple and consistent common framework. This facilitates interpretation and understanding of the implications of uncertainty in this setting. For policy makers and managers, the rule could be useful since regulators are often subject to several types of uncertainty at the same time. The rule provides a consistent foundation for aggregating these effects and evaluating the welfare implications of deviations from optimal instrument choice when this done for distributional or other reasons. The linear approximation of marginal functions that I use may be an advantage for practical application, since this seems to be a realistic framework for the estimations that managers must undertake in order to evaluate slopes and the different types of uncertainty that they face.

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Appendix A: Deriving equation (35) from equation (34)

Equation (34) is:

$$V^{\Phi*} = E_1\left[\theta\begin{pmatrix}(b+d)(R_1-Q_1^*)(\varepsilon_1+\tilde{\lambda}_1-\tilde{\theta})-½(b+d)(\varepsilon_1+\tilde{\lambda}_1-\tilde{\theta})^2\\+k(\varepsilon_1+\tilde{\lambda}_1-\tilde{\theta})R_1+(a\lambda_1-c)(\varepsilon_1+\tilde{\lambda}_1-\tilde{\theta})\end{pmatrix}\right]+V^{Q*}(S_0)$$

Since $\bar{R}_t+\varepsilon_t$ we have that:

$$V^{\Phi*} = E_1\left[\theta\begin{pmatrix}(b+d)(\bar{R}_t+\varepsilon_t-Q_1^*)(\varepsilon_1+\tilde{\lambda}_1-\tilde{\theta})-½(b+d)(\varepsilon_1+\tilde{\lambda}_1-\tilde{\theta})^2\\+k(\varepsilon_1+\tilde{\lambda}_1-\tilde{\theta})(\bar{R}_t+\varepsilon_t)+(a\lambda_1-c)(\varepsilon_1+\tilde{\lambda}_1-\tilde{\theta})\end{pmatrix}\right]+V^{Q*}(S_0)$$

Since $\tilde{\lambda}_t=(\lambda_t-1)a/b$ we have that $E\left[\tilde{\lambda}_t\right]=E\left[\varepsilon_t\right]=0$ and since $\tilde{\theta}=(1/\theta-1)\Phi_1/b$ we have that $\theta\tilde{\theta}=(1-\theta)\Phi_1/b$ so that $E\left[\theta\tilde{\theta}\right]=0$ while $E\left[\lambda_t\right]=1$ so that:

$$V^{\Phi*} = E_1\left[\theta\begin{pmatrix}(b+d)\varepsilon_t(\varepsilon_1+\tilde{\lambda}_1)-½(b+d)(\varepsilon_1+\tilde{\lambda}_1-\tilde{\theta})^2\\+k(\varepsilon_1+\tilde{\lambda}_1)\varepsilon_t+a\lambda_1(\varepsilon_1+\tilde{\lambda}_1)\end{pmatrix}\right]+V^{Q*}(S_0)$$

Since there is no covariance between θ and λ_t respectively ε_t we have that:

$$V^{\Phi*} = E_1\begin{bmatrix}(b+d)\varepsilon_t(\varepsilon_1+\tilde{\lambda}_1)-½(b+d)\theta(\varepsilon_1+\tilde{\lambda}_1-\tilde{\theta})^2\\+k(\varepsilon_1+\tilde{\lambda}_1)\varepsilon_t+a\lambda_1(\varepsilon_1+\tilde{\lambda}_1)\end{bmatrix}+V^{Q*}(S_0)$$

Factoring out we get:

$$V^{\Phi*} = E_1\begin{bmatrix}(b+d)(\varepsilon_1\varepsilon_1+\varepsilon_1\tilde{\lambda}_1)-½(b+d)(\varepsilon_1+\tilde{\lambda}_1)^2\\-½(b+d)\theta(\tilde{\theta})^2\\+k(\varepsilon_1\varepsilon_1+\varepsilon_t\tilde{\lambda}_1)+a(\varepsilon_1\lambda_1+\tilde{\lambda}_1\lambda_1)\end{bmatrix}+V^{Q*}(S_0)$$

Further factoring gets:

$$V^{\Phi*} = E_1 \begin{bmatrix} (b+d)(\varepsilon_1\varepsilon_1 + \varepsilon_1\tilde{\lambda}_1) \\ -½(b+d)(\varepsilon_1)^2 \\ -½(b+d)(\tilde{\lambda}_1)^2 \\ -(b+d)(\tilde{\lambda}_1\varepsilon_1) \\ -½(b+d)\theta(\tilde{\theta})^2 \\ +k(\varepsilon_1\varepsilon_1 + \varepsilon_t\tilde{\lambda}_1) + a(\varepsilon_1\lambda_1 + \tilde{\lambda}_1\lambda_1) \end{bmatrix} + V^{Q*}(S_0)$$

Rearranging we get:

$$V^{\Phi*} = E_1 \left[\begin{pmatrix} ½(b+d)(\varepsilon_1)^2 \\ -½(b+d)(\tilde{\lambda}_1)^2 \\ -½(b+d)\theta(\tilde{\theta})^2 \\ +k(\varepsilon_1\varepsilon_1 + \varepsilon_t\tilde{\lambda}_1) + a(\varepsilon_1\lambda_1 + \tilde{\lambda}_1\lambda_1) \end{pmatrix} \right] + V^{Q*}(S_0)$$

and further rearranging:

$$V^{\Phi*} = E_1 \left[\begin{pmatrix} ½(b+d+2k)(\varepsilon_1)^2 \\ -½(b+d)(\tilde{\lambda}_1)^2 \\ -½(b+d)\theta(\tilde{\theta})^2 \\ +k(\varepsilon_t\tilde{\lambda}_1) + a\varepsilon_1\lambda_1 + a\tilde{\lambda}_1\lambda_1) \end{pmatrix} \right] + V^{Q*}(S_0)$$

Adding $0 = a\mathrm{E}\left[-\tilde{\lambda}_t \right]$ we get:

$$V^{\Phi*} = E_1\left[\begin{pmatrix} ½(b+d+2k)(\varepsilon_1)^2 \\ -½(b+d)(\tilde{\lambda}_1)^2 \\ -½(b+d)\theta(\tilde{\theta})^2 \\ +k(\varepsilon_t\tilde{\lambda}_1)+a\varepsilon_1\lambda_1+a\tilde{\lambda}_1\lambda_1) \end{pmatrix}\right]+V^{Q*}(S_0)+a\mathrm{E}\left[-\tilde{\lambda}_t\right]=$$

$$E_1\left[\begin{pmatrix} ½(b+d+2k)(\varepsilon_1)^2 \\ -½(b+d)(\tilde{\lambda}_1)^2 \\ -½(b+d)\theta(\tilde{\theta})^2 \\ +k(\varepsilon_t\tilde{\lambda}_1)+a\varepsilon_1\lambda_1+a\tilde{\lambda}_1(\lambda_{t1}-1) \end{pmatrix}\right]+V^{Q*}(S_0)=$$

$$E_1\left[\begin{pmatrix} ½(b+d+2k)(\varepsilon_1)^2 \\ -½(b+d)(\tilde{\lambda}_1)^2 \\ -½(b+d)\theta(\tilde{\theta})^2 \\ +k(\varepsilon_t\tilde{\lambda}_1)+a\varepsilon_1\lambda_1+b\tilde{\lambda}_1(a/b)(\lambda_{t1}-1) \end{pmatrix}\right]+V^{Q*}(S_0)$$

Using $\tilde{\lambda}_t=(\lambda_t-1)a/b$ we get:

$$V^{\Phi*} = E_1\left[\begin{pmatrix} ½(b+d+2k)(\varepsilon_1)^2 \\ -½(b+d)(\tilde{\lambda}_1)^2 \\ -½(b+d)\theta(\tilde{\theta})^2 \\ +k(\varepsilon_t\tilde{\lambda}_1)+a\varepsilon_1\lambda_1+b\tilde{\lambda}_1\tilde{\lambda}_1 \end{pmatrix}\right]+V^{Q*}(S_0)=$$

$$E_1\left[\begin{pmatrix} ½(b+d+2k)(\varepsilon_1)^2 \\ ½(b-d)(\tilde{\lambda}_1)^2 \\ -½(b+d)\theta(\tilde{\theta})^2 \\ +k(\varepsilon_t\tilde{\lambda}_1)+a\varepsilon_1\lambda_1 \end{pmatrix}\right]+V^{Q*}(S_0)=$$

Adding $0=a\mathrm{E}\left[-\varepsilon_t\right]$ we get:

$$V^{\Phi*} = E_1\left[\begin{pmatrix} ½(b+d+2k)(\varepsilon_1)^2 \\ ½(b-d)(\tilde{\lambda}_1)^2 \\ -½(b+d)\theta(\tilde{\theta})^2 \\ +k(\varepsilon_t\tilde{\lambda}_1)+a\varepsilon_1\lambda_1) \end{pmatrix}\right] + V^{Q*}(S_0) + aE\left[\text{-}\varepsilon_1\right] =$$

$$E_1\left[\begin{pmatrix} ½(b+d+2k)(\varepsilon_1)^2 \\ ½(b-d)(\tilde{\lambda}_1)^2 \\ -½(b+d)\theta(\tilde{\theta})^2 \\ +k(\varepsilon_t\tilde{\lambda}_1)+a\varepsilon_1(\lambda_1-1) \end{pmatrix}\right] + V^{Q*}(S_0) =$$

$$E_1\left[\begin{pmatrix} ½(b+d+2k)(\varepsilon_1)^2 \\ ½(b-d)(\tilde{\lambda}_1)^2 \\ -½(b+d)\theta(\tilde{\theta})^2 \\ +k(\varepsilon_t\tilde{\lambda}_1)+b\varepsilon_1(\lambda_1-1)(a/b) \end{pmatrix}\right] + V^{Q*}(S_0) =$$

Using $\tilde{\lambda}_t = (\lambda_t - 1)a/b$ we get

$$V^{\Phi*} = E_1\left[\begin{pmatrix} ½(b+d+2k)(\varepsilon_1)^2 \\ ½(b-d)(\tilde{\lambda}_1)^2 \\ -½(b+d)\theta(\tilde{\theta})^2 \\ +k(\varepsilon_t\tilde{\lambda}_1)+b\varepsilon_1\tilde{\lambda}_1 \end{pmatrix}\right] + V^{Q*}(S_0) =$$

$$E_1\left[\begin{pmatrix} ½(b+d+2k)(\varepsilon_1)^2 \\ ½(b-d)(\tilde{\lambda}_1)^2 \\ -½(b+d)\theta(\tilde{\theta})^2 \\ +(b+k)(\varepsilon_t\tilde{\lambda}_1) \end{pmatrix}\right] + V^{Q*}(S_0)$$

Inserting $\tilde{\theta} = (1/\theta - 1)\Phi_1 / b$

$$V^{\Phi*} = E_1\left[\begin{pmatrix} ½(b+d+2k)(\varepsilon_1)^2 \\ ½(b-d)(\tilde{\lambda}_1)^2 \\ -½(b+d)\theta((1/\theta-1)\Phi_1/b)^2 \\ +(b+k)(\varepsilon_t\tilde{\lambda}_1) \end{pmatrix}\right] + V^{Q*}(S_0) =$$

$$E_1\left[\begin{pmatrix} ½(b+d+2k)(\varepsilon_1)^2 \\ ½(b-d)(\tilde{\lambda}_1)^2 \\ -½(b+d)\theta(1/\theta\theta+1-2/\theta)\Phi_1\Phi_1/bb) \\ +(b+k)(\varepsilon_t\tilde{\lambda}_1) \end{pmatrix}\right] + V^{Q*}(S_0) =$$

$$E_1\left[\begin{pmatrix} ½(b+d+2k)(\varepsilon_1)^2 \\ ½(b-d)(\tilde{\lambda}_1)^2 \\ -½(b+d)(1/\theta+\theta-2)\Phi_1\Phi_1/bb) \\ +(b+k)(\varepsilon_t\tilde{\lambda}_1) \end{pmatrix}\right] + V^{Q*}(S_0) =$$

$$\begin{pmatrix} ½(b+d+2k)E_1\left[(\varepsilon_1)^2\right] \\ ½(b-d)E_1\left[(\tilde{\lambda}_1)^2\right] \\ -½(b+d)E_1\left[(1/\theta+\theta-2)\Phi_1\Phi_1/bb)\right] \\ +(b+k)E_1\left[(\varepsilon_t\tilde{\lambda}_1)\right] \end{pmatrix} + V^{Q*}(S_0) =$$

$$\begin{pmatrix} ½(b+d+2k)E_1\left[(\varepsilon_1)^2\right] \\ ½(b-d)E_1\left[(\tilde{\lambda}_1)^2\right] \\ -½(b+d)(E_1\left[(1/\theta-1)\Phi_1\Phi_1/bb)\right] \\ +(b+k)E_1\left[(\varepsilon_t\tilde{\lambda}_1)\right] \end{pmatrix} + V^{Q*}(S_0)$$

Using $\tilde{\theta} = (1/\theta-1)\Phi_1/b$

$$V^{\Phi*} = \begin{pmatrix} ½(b+d+2k)E_1\left[(\varepsilon_1)^2\right] \\ ½(b-d)E_1\left[(\tilde{\lambda}_1)^2\right] - ½(b+d)E_1\left[\tilde{\theta}(\Phi_1/b)\right] \\ +(b+k)E_1\left[(\varepsilon_t\tilde{\lambda}_1)\right] \end{pmatrix} + V^{Q*}(S_0)$$

Which is equation(35.)

Appendix B: Implication for sign of *d* of a logistic growth function.

We consider the situation where economies of scale are small (*k=0*). Inserting (*k=0*) we know from (25) that optimal regulation in period 2 (irrespective of the instrument used) is set so that:

$$E\left[H_2^{I*}\right] = \bar{R}_2 + \frac{(a-c)}{(b+d)} \tag{B.1}$$

where the regulator observes S_1 prior to setting the instrument. Thus, irrespective of the instrument, it is optimal for the regulator to react to a change S_1 by adjusting the instrument so that expected harvest is adjusted by the same amount, i.e:

$$\frac{dE\left[H_2^{I*}\right]}{d\bar{R}_2} = 1$$

Which by (26), (27) and (30) for both instruments implies that:

$$\frac{dH_2^{I*}}{d\bar{R}_2} = 1$$

This and that $dR_2 / d\bar{R}_2 = 1$ implies that (37) reduces to:

$$\frac{dV^*(S_1)}{dH_1} = (b\bar{R}_2 + a)\frac{d\bar{R}_2}{dH_1^I} \tag{B.2}$$

When there are no economies of scale, instrument choice only effects the following period's profit. The intuition is that, when there are no scale economies, the stock that it is optimal to leave for the future at the end of period 2 does not depend on the initial stock in that period. Thus, the effect of changes in regulatory performance in period 1 accrues as profit in period 2, but does not affect periods 3 and so on because it is optimal to leave the same stock at the end of period 2, irrespective of the initial stock in that period. Inserting (B.2.) into (38) we have that:

$$d = -\alpha \frac{dV^2(S_1)}{d^2 H_1} = -\alpha b \left((\bar{R}_2 + a/b) \frac{d^2 \bar{R}_2}{d^2 H_1} + \frac{d\ \bar{R}_2}{d\ H_1} \frac{d\ \bar{R}_2}{d\ H_1} \right) \tag{B.3}$$

If the ecological growth function is linear, the second derivative is zero and since $\frac{d\ \bar{R}_2}{d\ H_1} < 0$ d will be negative. In the following, we assume that this basic biological reproduction relationship is given by a logistic function, i.e:

$$F(S_{t-1}) = S_{t-1} + hS_{t-1}(1 - \frac{S_{t-1}}{K}) \tag{B.4}$$

The logistic function, is a classic functional form which is commonly used in resource economics to capture the key characteristics of resource reproduction (h is growth rate and K is the so-called carrying capacity). Inserting the logistic reproduction relationship and normalizing K=1 we get:

$$\bar{R}_2 = (1+h)S_1 - hS_1^{\ 2}$$

So that:

$$\frac{d\ \bar{R}_2}{d\ H_1} = -1 - h + 2hS_1$$

This implies that:

$$\frac{d\ \bar{R}_2}{d\ H_1} \frac{d\ \bar{R}_2}{d\ H_1} = (-1 - h + 2hS_1)(-1 - h + 2hS_1)$$

$\Leftrightarrow$

$$\frac{d\ \bar{R}_2}{d\ H_1} \frac{d\ \bar{R}_2}{d\ H_1} = (1+h)^2 + 2hS_1 2hS_1 - 2hS(1+h)$$

$\Leftrightarrow$

$$\frac{d\ \bar{R}_2}{d\ H_1} \frac{d\ \bar{R}_2}{d\ H_1} = (1+h)^2 + 2h(hS_1^{\ 2} + hS_1^{\ 2} - S_1(1+h))$$

$\Leftrightarrow$

$$\frac{d\ \bar{R}_2}{d\ H_1} \frac{d\ \bar{R}_2}{d\ H_1} = (1+h)^2 + 2h(hS_1^{\ 2} - \bar{R}_2)$$

And that:

$$\frac{d^2 R_2}{d^2 H_1} = -2h$$

So inserting into (B.3) we have:

$$d = \alpha b\left((\bar{R}_2 + a/b)(2h) - ((1+h)^2 + 2h(hS_1{}^2 - \bar{R}_2))\right)$$
$$\Leftrightarrow$$
$$d = \alpha b\left(2h(\bar{R}_2 + a/b) - (1+h)^2 - 2h(hS_1{}^2 - \bar{R}_2)\right)$$
$$\Leftrightarrow$$
$$d = \alpha b\left(2h(2\bar{R}_2 + a/b - hS_1{}^2) - (1+h)^2\right)$$

So this is the shadow price in the optimal state (when all H2 and R2 values are optimal). What we are interested in is the slope of this curve as a function of H1. Remembering that this value is negative (a cost), a negative derivative will be a positive slope of the corresponding cost curve (here dR2/dH1 is negative). If we find a derivative of this curve which is numerically smaller than b (or a positive derivative), b is numerically greater than d.

We know a<0 so that:

$$d \le b\alpha\left(4h\bar{R}_2 - 2h^2\left(S_1\right)^2 - 1 - h^2 - 2h\right)$$
$$\Leftrightarrow$$
$$d \le b\alpha\left(2h(2\bar{R}_2 - 1) - 2h^2\left(\tfrac{1}{2} + S_1\right)^2) - 1\right)$$

The largest R=1 at carrying capacity the smallest S =½ at MSY so optimum is somewhere inbetween:

$$d \le b\alpha\left(2h(2*1-1) - 2h^2\left(\tfrac{1}{2}+\tfrac{1}{2}\right)^2) - 1\right) \Leftrightarrow$$

$$d \le b\alpha\left(2h - 2h^2 - 1\right) \Leftrightarrow$$

$$d \le b\alpha\left(2h(1-h) - 1\right) < 0$$

Thus a logistic growth function implies that d<0 when there are no economies of scale.