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Optimal Policy Structure in Natural Resource and Environmental Economics

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by

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ABSTRACT OF THE DISSERTATION

Optimal Policy Structure in Natural Resource and Environmental Economics

by

Jacob Sean LaRiviere

Doctor of Philosophy in Economics

University of California, San Diego, 2010

Professor Richard Carson, Chair

This dissertation consists of three separate papers that either derive optimal management strategies for environmental and natural resource management, develop theoretical models explaining observed effects government management of environmental and natural resources or both.

Chapter 1 shows that sharing arrangements between capital owners and labor in renewable resource industries have substantial implications for the industry's profits, optimal resource management, and the resource's ecological state. Effectively, sharing agreements can interact with fluctuations in natural capital to cause inefficient investment levels and skew industry rents toward labor. As a consequence, optimal regulatory policy for such industries must account for the implications of such sharing arrangements. The model demonstrates why management tools like individual transferable quotas in

fisheries, have had unexpected ecological benefits in terms of increasing and stabilizing fishery stocks.

Chapter 2 extends the research joint venture (RJV) literature to cover government funded energy-related collaborations between private firms and national laboratories. It uses a game theoretic framework to explain why a RJV including a national lab will tend to have significantly more participants than a private RJV. The model predicts that regulatory capture is likely to occur from firms that work with national labs in RJVs and receive exogenous funding, such as federal grants, to perform RJV research. Further, it is possible that RJVs including national labs that do not receive exogenous funding are more likely to consist of more heterogeneous firms.

Chapter 3 considers the implications on optimal pollution control when ambient levels of pollution are known but all emission sources are not. The model shows that if the dispersion models are misspecified due to incomplete inventories of emissions, optimal ambient pollution levels can actually increase. In this case, if R&D can increase the set of known emitters, a regulator may actually choose not to spend any resources to do as it can cause a decrease in expected welfare.

Chapter 1

Profit Sharing in Renewable Resource Industries: Implications and Optimal Management

Abstract

In renewable resource industries, labor is commonly paid with a share of the harvested resource rather than with a per unit-of-effort wage. Share cropping in agriculture is one well-known example and entitlement of the crew to a share of the revenue from the sale of the catch is almost universal among commercial fishing fleets. This paper shows that sharing arrangements have substantial implications for the industry's profits, optimal resource management, and the resource's ecological state. Effectively, sharing agreements can interact with fluctuations in natural capital to cause inefficient investment levels and skew industry rents toward labor. As a consequence, optimal regulatory policy for such industries must account for the implications of such sharing arrangements. The model demonstrates why management tools like individual transferable quotas in fisheries, have had unexpected ecological benefits in terms of increasing and stabilizing fishery stocks. Finally, the paper provides an illustrative example using the US Pacific albacore fishery.

1.1 Introduction

Firms in renewable resource industries typically pay labor exclusively as a percent of profit or revenue rather than with a per unit-of-effort wage. Such share arrangements exist in share cropping agreements, piece-rate logging contracts and catch share payments in fisheries. Standard textbook treatments (Clark 1990, Hartwick and Olewiler 1998 and Perman et. al. 1990) of the optimal management of renewable natural resources assume that revenue accrues unobstructed to the firm, as when labor is paid a fixed wage rate instead of the observed share remuneration structure. However, renewable resource management instruments conceived under the assumption of fixed wage payments instead of share remuneration regimes can lead to inefficient investment levels, forgone economic rents, and potentially sub-optimal harvesting rules. In some cases, the economic inefficiencies related to such suboptimal management directly lead to larger renewable resource stocks.

Firm revenues, or some function of firm profits, are generally split with labor in renewable resource industries, often accounting for labor's entire income. The form and size of the split varies across resource type, but labor's share of profit is substantial. In agricultural crop share arrangements in the Midwestern United States, the rule of thumb split between land owners and farmers is 50% of the agricultural yield (Allen and Lueck 1992). The vast majority of US groundfish troll fleets pay crew between 20-40% of the value of the catch less direct operating costs, such as bait and fuel, with vessel owners paying fixed costs.[1] On the other hand, piece rate timber contracts split revenue between firm owners and workers. In each case, labor receives no fixed wage component in their remuneration and is instead paid exclusively as a function of firm revenue. For the firm, then, the proportion of labor costs to revenues or profits is a large, constant term. By definition, share remuneration arrangements dramatically affect the rate of marginal revenue earned by firms over different levels of resource extraction.

There are two critical differences between renewable resource industries and other industries that makes implementing share contracts non-trivial. First, the size of resource harvest can vary greatly across time as a function of exogenous ecological conditions. Second, future resource stocks depend on current exploitation levels. A risk neutral

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[1] Surveys conducted jointly by US National Marine Fisheries Service (NFMS) and the Pacific States Marine Fisheries Commission between 2003 and 2006 show that roughly 98% of of troll fleets and open access groundfish and salmon fisheries off the west coast of the continental US pay the crew a share of revenue less operating costs.

firm in a renewable resource industry invests until its expected private marginal benefit of investment is equal to its expected private marginal cost. If there are externalities in the production process, such as the intertemporal effect of current period exploitation on future resource rents, then private costs do not reflect social costs. A resource regulator seeks to maximize the net present value of the resource by accounting for externalities, so that the firm's private costs equal social costs. However, when the rate of marginal benefit observed by the firm is affected by share remuneration of labor, the social marginal benefit of investment is no longer equal to the private marginal benefit of investment. Despite the resource manager's efforts, there is no guarantee that socially optimal industry-wide investment levels will be realized in the presence of share remuneration.

Where there is too little investment and forgone economic rents, though, there may be significant ecological gains. In the case of fisheries, too little investment caused by Individual Transferable Quotas (ITQs) management coupled with profit sharing labor remuneration induces larger breeding populations and fishery stocks. The share remuneration system in conjunction with policy instruments derived under the assumption of fixed wage remuneration induces a tradeoff between economic inefficiency and ecological gain which has implications for harvest targets and rules.

The influence of share remuneration contracts on renewable resource industry investment, profits and management has gone largely untouched in the economics literature with the exception of Hannesson (2000 and 2007). Hannesson (2000) shows via simulation that revenue sharing labor remuneration in ITQ managed fisheries may lead to over- or under-investment. This paper extends Hannesson's model to analyze the effect of the full linear class of profit sharing labor remuneration arrangements observed in practice on industry investment in all renewable resource industries. Analytical results of the model show the precise conditions under which each share system will lead to suboptimal investment in any resource management strategy conceived under the fixed per-unit-effort wage assumption. Hannesson (2007) shows that a quota tax will not solve the investment problem in ITQ fisheries stemming from revenue sharing but that an output tax will. This paper extends Hannesson (2007) in developing normative management accounting for share remuneration of labor for any choice of policy instrument when an optimal management is possible; the analysis shows that there are instances in which optimal investment is not possible due to the share remuneration structure. This paper provides empirical evidence that the potential size of the investment inefficiency caused by share remuneration of labor is at least 2% in the case of the US Pacific Albacore tuna fishery. Finally, this paper contributes to the renewable resource harvesting literature and finds that benchmark harvesting rules are no longer generally optimal in the presence of capacity constraints induced by share remuneration of labor.

The remainder of this paper proceeds as follows: section two offers a brief literature review of optimal renewable resource management and places previous research concerning share remuneration in context. Section three extends the fisheries model of Hannesson (2000) to incorporate all share contracts observed in renewable resource industries and introduces classical policy instruments designed to maximize economic rents from renewable resource extraction. This section also analytically evaluates the implications of the various share remuneration schemes on a firm's investment level. Section four simulates investment inefficiencies resulting from nave management policies. Section five offers normative policy accounting for profit sharing remuneration in renewable resource industries. Section six uses data from the Alaskan halibut and sablefish fisheries to illustrate the influence of remuneration agreements on industry level investment and the ecological benefits that can be associated from share remuneration in ITQ fisheries. This section performs a calibration exercise using data from the US Pacific albacore tuna troll fleet to show the lower-bound for the investment inefficiency caused by nave management. Section seven examines the intertemporal effects on the resource stock caused by investment inefficiency and shows that previously standard harvest rules might fail as a result. Section eight offers some concluding remarks.

1.2 Previous Literature

There is one intratemporal externality and one intertemporal externality associated with renewable resources, both of which motivate their management. The intratemporal externality concerns problems arising from ill-defined property rights leading to the commons problem while the intertemporal externality concerns maximizing long run expected resource rents. There is a large literature addressing both externalities asking which policy instrument is most efficient conditional on the ecological and economic environment as long as wage payments are fixed and exogenous. There is also a smaller unrelated literature which seeks to explain why share remuneration is observed in renewable resource industries. This section summarizes both lines of research in the context of the current paper.

There is considerable anthropogenic pressure on the world's renewable resources. World fisheries are in decline (Worm, et. al. 2008), deforestation is rampant (Granger et. al. 2002) and soil erosion from agricultural overuse is a concern (Lal 1999). In every case, the anthropogenic effects relate directly to economic market structures which lead individuals to overexploit the resource. Classifying renewable resources as common property is one common market structure which leads to ecological over-exploitation of renewable resources.

In a certain world, it is well understood that externalities leading to the commons problem in renewable resource industries may be efficiently remedied by taxes or the enforcement of property rights (Gordon 1954 and Schlager and Ostrom 1992). Either prices or quantities can be an efficient policy instrument so long as they equate private costs of the firm with social costs to eliminate the dissipation of rents associated with common property. Further, Weitzman (1974), Weitzman (2002) and Hannesson and Kennedy (2005) all examine whether quantities or prices serve as the best regulatory tool in the presence of different types of ecological and economic uncertainty given exogenous wage payments in renewable resource industries. Even in cases where property rights exist in name, lack of enforcement can create de facto common property requiring additional policy instruments for optimal management of fisheries, forestry, agriculture and water (Sjostedt and Taylor 2007). In every case, though, existing literature assumes labor is remunerated as a fixed wage and revenue accrues unobstructed to the firm. If labor is remunerated as a share of profit, then the regulatory problem is misspecified and could lead to inefficient outcomes. Hannesson (2000) is the only research addressing the share remuneration issue in renewable resource management. His work shows that revenue sharing in a fishery with ITQs may lead to suboptimal investment in physical capital.

The intra-period externality which leads to overexploitation of renewable resources is related to the inter-period effect which can cause long run resource stock overexploitation. Complex and idiosyncratic ecological relationships dictate how fast renewable resources grow over time. Disease, cyclical ecological conditions and technological change all have implications for resource harvest rates (Condeso and Meentemeyer 2007, Carson et. al. 2008 and Murray 2008). The collapse of many fisheries is one clear example of overexploitation of renewable resources, but some forestry and agricultural practices have adversely affected the ecological state of forests and topsoil quality (Worm et. al. 2009, Costello et. al. 2009, Pimental et. al. 1995, Rodrigues, et. al. 2009). Choosing how much of a renewable resource to exploit every period can be a difficult task and complicated interdependent ecosystems can make the problem even more difficult. As such, many nations have developed regulatory bodies that collect all relevant information and oversee the rate at which renewable resources are exploited every year. Even when harvest rates are determined by a regulator, though, policy instruments still may matter. Costello et. al. (2009) shows that ITQ managed fisheries are healthier than those managed solely with catch limits.

The precautionary principle as developed in Arrow and Fisher (1974) is potentially the most well known intertemporal environmental management rule. The precautionary principle states that it is optimal to exploit less of a renewable resource when there is a positive possibility of resource stock collapse. Using a different model, Reed (1979) shows that so long as there are no industry capacity constraints, a regulator should harvest the resource stock down to a level that is a function of ecological parameters, but never past it. Costello and Polasky (2008) and Sethi et. al. (2005) extend Reed's model to incorporate complicated ecological relationships and find that Reed's "constant escapement policy" continues to be optimal.

Other intertemporal relationships in renewable resources have been shown to induce managers to combine policy instruments. Pizer (2002) has shown that there may be benefits to using hybrid regulatory policies for climate change in the case of price uncertainty. Smith (2009) shows that high-grading behavior in fisheries, the practice of dumping low value fish for high value fish can be eliminated by using a tax in conjunction with ITQs.[2] In every case, either economic or ecological uncertainty merits a combination of policy instruments to control for externalities associated with renewable resources.

A small and unrelated literature which examines the motivations for implementing a share remuneration system in renewable resource industries. The existence of share remuneration arrangements has been attributed to both risk-sharing by firm owners and a solution to principal-agent moral hazard problems. The risk-sharing explanation for share labor payments is deeply entrenched in the crop sharing literature and has been studied with respect to fisheries as well. Cheung (1969) developed a model further analyzed by Allen and Lueck (1999) showing that in natural resource industries with highly variable output, share remuneration reduces the variability of income to the principal.

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[2] Hannesson 2007 also considers a directly related hybrid regulatory policy that is discussed below.

Plourde and Smith (1989) use a similar argument to explain share contracts in fisheries. Share remuneration in renewable resource industries is also attributed to ameliorating the moral hazard problem of non-contractible effort in a principle-agent setting. This explanation has received considerable attention in the share-cropping, piece-rate forestry and fisheries literatures (Allen and Lueck 1992, Gibbons 1987, McConnell and Price 2006). In each case, this sphere of research examines firm level outcomes such as productivity or optimal share levels.

While the firm level implications of share remuneration have been considered in the literature, little work examines the industry level effects implementing a share remuneration structure in renewable resource economics.[3] Share remuneration in renewable resource industries affect industry level outcomes, and thus merit study, for three reasons. First, incomplete or unenforced property rights in renewable resource industries often leads regulators to use policy instruments such as taxes, property rights, harvest limits and command and control production techniques to maximize long run resource rents and ensure resource stock health. If the regulator does not account explicitly for the remuneration structure to labor in designing their policy instruments, the interaction of these policy instruments amounts to a specification error in the regulator's problem. Second, there is significant ecological variability due to natural and anthropogenic idiosyncrasies that affect the exploitation of renewable resources. As such, altering the rate of profit flows to firm owners by implementing share labor contracts changes incentives to invest.[4] Third, any within period inefficiencies are magnified in renewable natural resource industries since resource stock levels are intertemporally related.

The implications of paying labor as a share of profits or as a share of revenues on the management and profitability of renewable resources industries have received little attention in the economics literature. McConnell and Price (2006) show that unaccounted for share remuneration regimes leads to important implications for econometric estimation of fishery production functions.[5] Hannesson (2000 and 2007) is the first and

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[3] Weitzman (1983 and 1985) examines the macroeconomic implications of remunerating labor by some form of profit sharing as opposed to fixed wage payments. The main theoretical result of these papers is that there are desirable increases in employment and production levels within firms and the macroeconomy. Under some conditions, Nordhaus (1988) finds that these results do not hold.

[4] For example, consider a tax on profits in a renewable resource industry. The tax will clearly lower investment in the industry, leading to too little investment and forgone resource rents.

[5] There is a small literature studying how the adoption of ITQ management affects remuneration structure and crew earnings. Casey et. al. (1995) observes that upon implementing ITQ management in the Alaskan Halibut fishery, crew remuneration shares were kept constant in well over half of the vessels and crew shares went up or down in roughly equal proportions on other vessels. Knapp (2006) examines

only work to analyze the share remuneration issue as it relates to industry level outcomes and resource management. Hannesson (2000) shows that revenue sharing in a fishery managed by ITQs may lead to suboptimal investment in physical capital. Hannesson (2007) shows that only with an appropriate landings tax will ITQs lead to optimal investment in a revenue sharing fishery. In essence, Hannesson (2000 and 2007) identifies a particular case in which augmenting the flow of revenue to firm owners can change investment decisions and that only some policy instruments can take this into account.

1.3 A Simple Model of Renewable Resource Industries

Consider a model of renewable resource extraction in which the size of the available resource harvest is subject to some uncertainty. Such is the case in farming where yield is subject to some climate variability, forestry in which case the amount of forest to be harvested or seeded varies with idiosyncratic shocks like disease or weather and a fishery managed with an idiosyncratic total allowable catch (TAC) due to dynamic ecological factors (see Sethi et. al. 2005 Carson et. al. 2008). For the purpose of exposition, we use the example of fisheries managed with TAC limits, which is a typical arrangement in the United States and many other countries. In a TAC managed fishery, the regulator is able to observe the catch of all vessels in the fishery. When the sum of all the vessels catch equals the TAC set by the regulator for that season, the fishery is shut down. TAC managed fisheries are open access, meaning that anyone who registers with the regulatory body overseeing the fishery may enter. As a result, TAC managed fisheries suffer from the commons problem. The TAC in a given period, t, is assumed to be the realization of a random variable with an associated time invariant pdf $f(\cdot)$.

Following Hannesson (2000), consider a model in which there are N_t homogeneous firms in an industry at time t. Each firm has some production capacity k which is invariant across time. Firms are assumed to have some capital cost K, some depreciation rate d and subject to some rental rate r. More generally, $K(r+d)$ can be thought of as the yearly fixed cost of lumpy physical capital units which must be used in the renewable resource extraction process. Note that capital investment is assumed to have a cost every

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the effect of quotas on employment in the Alaska Crab fishery, but not in the context of remuneration structure. Brandt and Ding (2008) examine the implication of ITQs in the mid-Atlantic surf clam fishery and find no statistically significant effect on pay. Abbott, Barber-Yonts and Wilen (2009) find that remuneration shares stay roughly constant in Alaskan crab fisheries after the implementation of ITQs.

period, irrespective of whether the capital is used in the period. Further, in this model, market participants cannot substitute between capital and labor. Rather, firms choose a vessel size whose productivity is maximized for a given crew size. These assumptions are somewhat restrictive but not entirely unreasonable in renewable resource industries. Casey et. al. (1995), Brandt and Ding (2008) and Abbott et. al. (2009) each find almost no significant changes in per boat crew sizes, or share levels, in fisheries that switch between open access TAC management and ITQ management.

In agriculture, potential crop harvest is dictated by climate and in both forestry and fisheries harvest is usually set by a resource manager respond to ecological variations. In the model, the amount of natural capital available for harvest in a period t is represented by Q_t. Q_t is a random variable drawn from a time invariant distribution $f\cdot$ which has bounded support $[Q_{min}, Q_{max}]$. The distribution $f(\cdot)$ can be thought of as the distribution of a resource stock which incorporates equilibrium ecological and economic variables such that long run industry profits are maximized. As a result of the homogeneity assumption, the resource stock Q_t is split evenly among firms such that production per firm in year t is $min[k, \frac{Q_t}{N_t}]$ where k is firm level capacity.

In the model, firms make a one-time entry decision. Since the distribution of natural capital is fixed across time, though, the entry decision is redundant from one period to the next as long as prices, p, are assumed to be constant. For simplicity, assume time invariant operating costs , c, and time invariant physical capital factor payments, $(d + r)K$, must be paid by the firm.[6] In the baseline case, assume that labor is paid with a standard fixed wage rate, w. Given these assumptions, the expected profit in the fishery described above is given by

$$EV = (p - c)\left[\int_{Q_{min}}^{kN} Qf(Q)d(Q) + kN(1 - F(kN))\right] - (d + r)KN - wN \tag{1.1}$$

Using the example of a TAC managed fishery, the first term with the brackets represents the average industry catch when the TAC is below fleet capacity kN and the second term represents the proportion of the time the TAC exceeds the fleet's harvest capacity. The total industry wage bill, wN, will take different forms depending on which remuneration regimes, either parametric wages, scale wages or profit sharing- is modeled. This will become clear as different remuneration regimes are introduced below.

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[6] All the analysis in this section go through if unit costs are decreasing in resource stock size. In some cases the results are magnified. In any case, constant unit costs are assumed so as to highlight the nature of the inefficiencies which can result from share remuneration.

1.3.1 Different Share Remuneration Regimes

The different remuneration regimes to be analyzed are introduced in this section. All share regimes are assumed to be linear in either revenue, operating profits or total profits.[7]

Scale Wages

Hannesson (2000) considers a special case of renewable resource property rights management, the ITQ managed fishery. In the Hannesson model, the right to harvest quota is evenly allocated across a fleet, and firms pay labor as a share of total revenue. This is precisely the piece-rate structure common in forestry. In this remuneration regime, capital owners earn a share of the gross revenue, $x \in (0,1)$, leaving labor a share of size $(1-x)$. In this case, an individual firm owner has expected revenue of

$$EV = (px - c)\left[\int_{Q_{min}}^{kN} \frac{Q}{N} f(Q)d(Q) + k(1 - F(kN))\right] - (d+r)K. \tag{1.2}$$

Note in equation 2 that the wage term has been replaced by the share of gross profit which accrues to the firm owner.[8] As a result, labor's total expected remuneration, $E[M|x]$ for a given season equals

$$E[M|x] = p(1-x)\left[\int_{Q_{min}}^{kN} \frac{Q}{N} f(Q)d(Q) + k(1 - F(kN))\right] > w. \tag{1.3}$$

It is important to recognize that in any remuneration regimes, labor's expected remuneration must be at least as large as their opportunity wage, w. Note that it could be the case that equation 3 could constrain and determine the industry's production capacity, kN.[9] Further, while economic theory derived in McConnell and Price (2006) suggests that firms choose a remuneration structure and share sizes to maximize their own profits in fisheries, the NFMS and PSMFC surveys mentioned above show a large amount of variation in remuneration regimes both within and across fisheries.[10] To

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[7] Non-linear share structures, such as a fixed wage rate with bonus pay tied to resource harvest are briefly considered in the simulation section below but are generally beyond the scope of this paper.

[8] For notational ease, for the remainder of the paper, it shall be assumed the $kN \leq Q_{max}$.

[9] Indeed, labor's participation constraint may be why this subject received little attention in the past: there is no counterfactual where labor does not participate in a renewable resource industry, by definition.

[10] There are at least two explanations for this finding. First, there could be substantial heterogeneity with respect to vessel/crew ability or information sets. This could lead to different values of x being optimal for different owners. Second, individual vessel owners may behave sub-optimally by conforming

simplify the exposition here we will take the firm's share, x, as given and not the result of a richer dynamic optimization problem.

Operating/Full Profit Sharing

Now consider an operating profit sharing labor remuneration regime common in most OECD fisheries. 98% of west coast troll fisheries and many sharecropping agreements in developing countries remunerate labor by share revenue less direct operating costs. In such regimes, the crew is usually paid as a share of the operating profit (e.g., the profit excluding capital rental costs). In this case, the expected revenue accruing to the firm owner would be

$$EV = x(p-c)\left[\int_{Q_{min}}^{kN} \frac{Q}{N} f(Q)d(Q) + k(1-F(kN))\right] - (d+r)K. \tag{1.4}$$

Here, x is the share of profit which accrues to the firm owner. In this case, labor's expected share of the profit simply equals

$$E[M|x] = (1-x)(p-c)\left[\int_{Q_{min}}^{kN} \frac{Q}{N} f(Q)d(Q) + k(1-F(kN))\right] \geq w. \tag{1.5}$$

In the case of full profit sharing, a firm maximizing expected profits will take into account that capital rental costs are being shared with labor.[11] Full profit sharing was found to be present in many artisinal fishing communities studied by McClanahan and Mangi (2001).[12]

Profit Sharing with Feedbacks

It is possible that as the share of the profit to be received by labor increases, labor will work harder to increase the profit margin per unit of production in order to increase their own pay. This feedback effect explored by McConnell and Price (2006) could confound the yield per unit effort if effort is endogenously determined with the

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to industry norms and fail to adjust this parameter. In support of this second claim, Casey et. al. (1995) shows that over half of halibut fishing vessels did not change remuneration regimes in response to the transition from open access to ITQ management. Abbott et al. (2009) finds the same stability in Alaskan crab fisheries.

[11] Formally, this amounts to $EV = x(p-c)\left[\int_{Q_{min}}^{kN} \frac{Q}{N} f(Q)d(Q) + k(1-F(kN)) - (d+r)K\right]$.

[12] Note that full profit sharing results in the maximum amount of risk sharing for firm owners. As such it is not surprising that we observe this remuneration structure in highly variable stocks.

scale wage. Since effort decisions are not made without considering the profit share, fee management could become more difficult to optimally implement since setting an optimal fee becomes increasingly complicated.

Consider a profit sharing remuneration regime where the percent of operating profit which accrues to the crew, $(1-x)$, endogenously affects labor's effort and in turn the firm's unit costs. For the exposition that follows we consider a fishery although the same model can clearly be applied to forestry or agriculture.

In the fishery, the expected revenue accruing to the vessel owner under profit sharing with feedback effects is

$$EV = x\left[(p-c(e))\left[\int_{Q_{min}}^{kN}\frac{Q}{N}f(Q)d(Q)+k(1-F(kN))\right]\right]-(d+r)K. \tag{1.6}$$

Here, $c(e)$ is a strictly convex function representing the marginal per unit cost of fishing, with e representing crew effort. The accompanying expected crew remuneration in this model is

$$E[M|x] = (1-x)\left[(p-c(e))\left[\int_{Q_{min}}^{kN}\frac{Q}{N}f(Q)d(Q)+k(1-F(kN))\right]\right] \geq w. \tag{1.7}$$

In this model, costs are not parametric but rather a function of effort, e which will be endogenously chosen by the crew. The precise form of the crew's maximization problem is elaborated upon in appendix A. As a result, the remuneration parameter 'x' could have a feedback effect on the productivity of the fishing vessel. In this extension, crew member productivity will be inversely related to the operating cost of the vessel in equilibrium. Thus, time at sea, fuel use and time to the processor might all be reduced if remuneration rates are increased in a model with scale wage feedbacks.[13] Note that the crew's share $(1-x)$ is multiplying total operating profits.

1.3.2 Different Management Regimes

Renewable resource management is needed most in the absence of well-defined property rights. In open access fisheries and agricultural production in less developed countries, economic rents can be dissipated due to poor enforcement of property rights.

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[13] Time to the processor might actually affect price, but a more general notion of profit per unit of fish subsidies this issue. Therefore, nothing is lost by assuming all benefits accrue through cost.

In the absence of establishing enforceable property rights, taxes or fees may be used as a policy instrument to affect entry and investment into the industry. This subsection introduces three policies- property rights, taxes on price and taxes on capital- which may lead to optimal renewable resource management. Given that firms are homogeneous in this model, resource rents are maximized for a given industry size, N. Therefore, optimal renewable resource management is defined as management that induces the optimal industry size. To this end, the absence of any management and optimal management are introduced as benchmark cases. This section introduces property rights, output taxes and capital taxes derived under a fixed wage assumption and derives analytical results for the influence of such policy instruments on resource rents and labor outcomes.

Open Access

It is well known that open access to a renewable resource leads to a full dissipation of economic rents. Under open access entry an investment will occur until the expected economic profit of entry is zero. Thus, setting the expected value of the resource, represented by equations 1, 2, 4 and 6, equal to zero will implicitly define the equilibrium number of firms in open access under the four different share remuneration regimes.

Optimal Management

In this model, the social planner maximizes the expected annual profit of the renewable resource with respect to the number of firms in the industry. The reason why the capacity issue is relevant is that there is annual variation in the natural resource stock available for exploitation but yearly fixed costs of capital. As such, over-investment implies that the industry is paying too much in yearly capital costs relative to the natural resource stock's distribution. The canonical example of over-investment is fleet capacity in a fishery. Treating the number of firms as a continuous variable, the maximization problem for the social planner amounts to maximizing expected revenue, equation 1, with respect to N. As shown in Hannesson (2000), Liebnitzs' rule yields the first order condition

$$(p-c)k(1-F(kN)) = (d+r)K + w. \tag{1.8}$$

This equation shows that the expected marginal revenue of an additional firm must equal the marginal social cost of adding another firm in equilibrium under optimal management. Note that in both the case of profit sharing or exogenous wage payments, it need not be the case that total production capacity equals the maximum amount of natural capital to be exploited. Given that physical capital payments must be made in each period, if the chance of a very large exploitable natural capital stock is small, it may not be efficient from the social planners perspective to invest in additional capacity that may only rarely be used. Put more precisely, if the percentage of time the fleet capacity will be exceeded is small, $(1 - F(kN))$, then the frequency with which the marginal firm will be needed to reach the available resource stock will be small.

Property Rights

Establishing enforceable property rights is perhaps the most attractive method of regulating a renewable natural resource. In the case of the timber industry, different sections of forest are auctioned off to be harvested by logging companies. Upon winning a contract, the company has exclusive use rights over the resource in that area. A similar arrangement arises with share-cropping in the developed world. This section uses ITQ managed fisheries as a concrete example of property rights management.

Equilibrium in the ITQ system is defined as the point at which the owner of one ITQ gains the same revenue from either selling the ITQ or fishing. Assume that a quota is evenly distributed across the fleet such that each boat receives $\frac{1}{N}$ of the TAC Q_t set by the regulator. If an owner of quota size $\frac{1}{N}$ wishes to cease fishing and sell her quota to the remaining boat owners, she maximizes sale revenue when she sells equal quota shares to all vessel owners who remain in the fishery. Therefore, the sum of each vessel owner's willingness to pay for additional quota is the sum of each firm's expected increase in profits if one vessel exits and its quota is evenly split among remaining vessels. Equilibrium is reaches when the value from quota sale is equal to the value of continue fishing.

ITQ regimes are well understood when crews are paid a parametric wage and lead to efficient outcomes. However, Hannesson (2000) shows that ITQ management with a revenue sharing may lead to excessive or insufficient fleet capacity. Taking the case of operating profit sharing, the sum of the industry's willingness to pay for additional quota is given by:

$$-N\frac{\partial ER}{\partial N} = x(p-c)\int_{Q_{min}}^{min[kN,Q_{max}]}\frac{Q}{N}f(Q)d(Q). \tag{1.9}$$

Intuitively, the willingness to pay for additional quota of the vessel owners who stay in the fishery is equal to the increase in expected profit they gain by purchasing the quota. Boat owners gain from purchasing additional ITQ only when their catch share is less than vessel capacity, $Q_t/N < k$.

For a given share level, x, in ITQ management equilibrium the the expected revenue from selling quota to existing vessels must be equal to the expected revenue from continued fishing. This condition is represented by setting equation 9 equal to equation 4, which after some algebraic manipulation yields

$$x(p-c)k(1-F(kN)) = (d+r)K. \tag{1.10}$$

Equation 10 implicitly defines industry size, N, as a function of the firm's share, x, and other parameters. Therefore, given the motonicity of $F(\cdot)$, N is increasing x in equilibrium as long as labor's participation constraint is satisfied. Intuitively, as the share accruing to the firm rises, the economic value of continued harvesting rises faster than the revenue from selling the property right because purchasing additional quota is only worthwhile when a firm harvest is below firm capacity, $Q_t/N < k$, due to the homogeneity assumption. As a result, additional firms enter by buying the right to harvest up to the point where the operating profit earned by capital owners equals the price which they could earn by selling the property right and exiting the industry.

Taxes on Output

An ideal tax regime lowers the resource price to the point where the expected economic profit of adding capital is zero at the social planner's optimum production capacity.

In order to calculate an optimal tax, the regulator must increase the cost of additional production capacity such that firms earn zero expected economic profit at the rent maximizing production capacity. Again, using fisheries management as an example, assume that TAC varies randomly according to $f(Q)$. As a result, the social planner must choose a percent of tax on the price to be paid at landing of τ such that the expected profit of an additional boat is zero if N is at its optimal level as defined by equation 1, N^*:

$$((1-\tau)p-c)\left[\int_{Q_{min}}^{kN^*} \frac{Q}{N^*} f(Q)d(Q) + k(1-F(kN^*))\right] - (d+r)K - w = 0. \tag{1.11}$$

Implicitly defines τ as a function of the parameters of the particular fishery where N^* is the fleet capacity which comes from maximizing industry profits with respect to N (e.g., the social planner's choice of N).

Firm Licensing Fee/Tax on Capital

Enforceable property rights are not plausible in many remote fisheries and marginal agricultural land in the developing world. Where property rights enforcement is costly, price instrument can be an effective management tool. An ideal firm licensing fee or capital tax management regime in the model would raise the per period cost of capital to the point where the expected economic profit of an entering firm is zero at the social planner's production capacity. If Φ is taken to be the licensing fee, then the optimal fee is implicitly defined by the equation

$$(p-c)\left[\int_{Q_{min}}^{kN^*}\frac{Q}{N^*}f(Q)d(Q)+k(1-F(kN^*))\right]-(d+r+\Phi)K-w=0 \tag{1.12}$$

1.3.3 Analysis

Regulatory policy constructed under the assumption of fixed wage payments in renewable resource industries using share remuneration will often lead to inefficient levels of investment in the industry. This subsection presents analytical results for different combinations of remuneration regimes and naively designed regulation. The inefficiencies associated with property rights management are presented first, followed by taxes on output and capital.

First consider equilibrium under property rights management in an industry using operating profit share remuneration, such as as with many ITQ managed fisheries. Equilibrium industry capacity, given fixed wage, remuneration is implicitly defined by equation (1.8) under property rights management and by equation (1.10) if labor is remunerated by operating profit sharing. Rearranging terms, the following set of equations show equilibrium industry capacity in each case, with N^* representing optimal industry size under fixed wage remuneration and N^{OP} representing equilibrium industry size under operating profit sharing remuneration:

$$\begin{aligned}(p-c)k(1-F(kN^*) &= (d+r)K+w &\quad(1.13)\\ x(p-c)k(1-F(kN^{OP})) &= (d+r)K &\quad(1.14)\end{aligned}$$

These two equations immediately lead to the following proposition.

Proposition 1:

If labor earns at least their opportunity wage and the cdf of resource harvest is strictly monotonic, operating profit sharing remuneration in conjunction with property rights management leads to an efficient industry size only if the share that accrues to firms equals the capital cost's share of total costs.

Proof. Equation (13) is the property rights equilibrium condition with fixed wage payments and equation (14) is the property rights equilibrium condition under operating profit remuneration with N^{OP} the according equilibrium fleet capacity. Since the cdf, $F(\cdot)$ is assumed to be strictly monotonic, there is a unique industry capacity which satisfies equation 13. Impose $N^{OP} = N^*$ and divide equation (14) by equation (13). The condition under which sharing operating profit property rights management will give the optimal fleet capacity:

$$\frac{(r+d)K}{(r+d)K+w} = x \tag{1.15}$$

This expression gives the desired result. $Q.E.D.$

For any set of parameters, then, there exists a unique share level, x, which leads to optimal industry size. However, there is no reason why the share that accrues to capital owners must equal the unique share level which guarantees optimality in general. If the share accruing to a harvest-right owner is less than the capital cost share, it means that the value of fishing for the capital owner is too little relative to their capital contribution to the production process and investment is too low relative to the optimum. On the other hand, as the marginal value of harvesting increases via quota owners' share increasing, firms stay in the industry until there is over-investment.

Thus far, we have assumed that labor's remuneration constraint does not bind in the analysis. However, for a given share level, x, optimal industry might not be attainable without violating labor's participation constraint. In order to determine the effect of a binding remuneration constraint on investment, again compare the equilibrium condition in operating profit sharing with property rights management, equation (1.14), and the equilibrium condition under optimal management, equation (1.8). Property rights management coupled with operating profit remuneration optimal investment when the remuneration level when each vessel is operating at capacity is equal to the opportunity wage of labor:

$$(p-c)(1-x)k(1-F(kN)) = w. \tag{1.16}$$

The proper interpretation of equation (1.16) is that the wage w given in the labor market must be equal to labor's remuneration when the fleet is fishing at full capacity. However, the harvest level in any period, Q_t, is the realization of a random variable. If the share wage paid to the labor, $(1-x)$, was determined by the labor market, such that expected crew remuneration was equal to the opportunity wage, the $(1-x)$ would be defined in the equation

$$(p-c)(1-x)\left[\int_{Q_{min}}^{min[kN,Q_{max}]} \frac{Q}{N} f(Q)d(Q) + k(1-F(min[kN,Q_{max}]))\right] = w. \tag{1.17}$$

However, as long as $\int_{Q_{min}}^{min[kN,Q_{max}]} Qf(Q)d(Q) > 0$, it must be the case that the wage condition in equation (1.16) is less than the expected wage share given in equation (1.17).[14] Thus, as the probability of resource harvests below a given level of industry harvest capacity increases, the larger the difference between the expected share remuneration and the opportunity wage. Put another way, as the likelihood of realizing harvests below the industry capacity increases, the distortion caused by share remuneration increases. As such, increased variation in the renewable natural resource will lead to increasing distortion if labor is remunerated as a share of operating profit. Hannesson (2000 and 2007) finds a similar result in the case of revenue sharing in ITQ managed fisheries.

If the expected remuneration of labor is less than or greater than the opportunity wage, then the labor market is in disequilibrium. This can be examined analytically in the operating profit sharing model. The result of the analysis is the following proposition.

Proposition 2:

In an operating profit sharing regime under property rights management, labor's expected remuneration is always above their opportunity wage at optimal fleet capacity as long as the resource harvest size varies and is dictated by a continuous and strictly monotonic cdf.

A full proof is in the Appendix but the intuition is as follows: labor is paid a share of operating profits at every level of production and not just at the maximum

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[14] If the crew is risk loving or risk averse, expected remuneration will be less than or more than the opportunity wage, respectively.

production capacity or at the investment margin. At the optimal industry size the firm's expected operating profit is less than the amount there would have been had labor been remunerated with a fixed wage because firms share profits even when the realized harvest is low. This creates a rent transfer to those laborers who stay in the industry but leaves those who exit earning the opportunity wage determined by the broader labor market. The only way that there can be an efficient level of investment is if labor earns resource rents.

Next consider the case of full profit sharing in a property right management structure where firms share capital costs with labor. Such is the case in many artisinal fisheries. As with operating profit sharing, equilibrium industry capacity is implicitly defined when the expected profit from continued operation is equal to the income earned by selling the harvest-right. This condition is satisfied when

$$\begin{aligned} x(p-c) & \int_{Q_{min}}^{min[kN,Q_{max}]} \frac{Q}{N} f(Q)d(Q) \\ = & \quad x(p-c)\left[\int_{Q_{min}}^{kN} \frac{Q}{N} f(Q)d(Q) + k(1-F(kN)) - (d+r)K\right]. \end{aligned} \tag{1.18}$$

This equilibrium condition will always lead to overinvestment relative to the social planner's optimum if labor's remuneration constraint does not bind.

Proposition 3:

In a full profit sharing regime under property rights management, as long as the cdf of resource stock harvest is strictly monotonic, there will always be overinvestment in the industry so long as the labor's remuneration constraint does not bind. If the remuneration constraint binds, there is a unique point which leads to optimal investment.

Proof: Equation (1.18) can be rearranged such that

$$\left(1 - \frac{(d+r)K}{(p-c)k}\right) = F(k\tilde{N}). \tag{1.19}$$

Comparing equation (1.19) to the same rearrangement of the social planner's equilibrium condition with a fixed wage:

$$\left(1 - \frac{w+(d+r)K}{(p-c)k}\right) = F(kN^*) < \left(1 - \frac{(d+r)K}{(p-c)k}\right) = F(k\tilde{N})). \tag{1.20}$$

As long as the opportunity wage is non-zero and the cdf of the resource stock harvest is monotonic, then $N^* < \tilde{N}$. If the level industry investment is dictated by the remuneration constraint, then investment is dictated by

$$E[M|x] = (1-x)\left[(p-c)\left[\int_{Q_{min}}^{k\tilde{N}} \frac{Q}{\tilde{N}} f(Q)d(Q) + k(1-F(k\tilde{N}))\right] - (d+r)K\right] = w. \tag{1.21}$$

Assume that $N^* = \tilde{N}$. Given this equilibrium condition and using the optimal investment equilibrium condition, optimal investment is achieved when

$$\int_{Q_{min}}^{kN^*} \frac{Q}{N^*} f(Q)d(Q) + k(1-F(kN^*)) = w\frac{x}{(1-x)}. \tag{1.22}$$

Since the function $\frac{x}{(1-x)}$ is monotonic and maps from $[0,1) \Rightarrow \Re^+$, there is a unique x which solves equation (1.22). *Q.E.D.*

Intuitively, the reason why there may be overinvestment in the absence of a binding remuneration constraint is that the firm is able to share capital costs with labor. When the capital owners' share is sufficiently high so that labor's remuneration constraint is not satisfied, firms must exit until labor's share meets their reservation wage. Therefore, investment is driven down until it passes through the social planner's optimum investment level. At share levels below the unique amount which may lead to optimal investment there is underinvestment and at share levels above this amount, there is overinvestment.

Property rights management in conjunction with revenue sharing remuneration has the same rent sharing implications as operating profit sharing remuneration developed in proposition 2.[15] The share level under which revenue sharing arrangement leads to optimal fleet capacity is given by

$$\frac{p-c}{px-c} = 1 + \frac{w}{(d+r)K}. \tag{1.23}$$

This expression shows the inverse relationship between labor's reservation wage and the share level which gives optimal fleet capacity. As the reservation wage moves toward zero, the revenue which must accrue to the capital owner in order to ensure optimal investment approaches one. As in the previous cases, if the remuneration constraint

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[15] This is the remuneration and management pairing examined by Hannesson (2000) using simulation techniques, although Hannesson 2000 focused specifically on ITQ managed fisheries.

binds, then equilibrium investment is determined by labor's expected remuneration being equivalent to the reservation wage, and optimal fleet capacity may not be realized.

Now consider using price instruments constructed under the assumption of fixed wage payments to alleviate the dissipation of rents caused by the lack of enforceable property rights. If labor is remunerated with fixed wage payments, price instruments can be more desirable than quantity instruments in the case of significant ecological uncertainty or if costs of property rights enforcement is high (Weitzman 2002). In constructing optimal taxes, a regulator changes the prices observed by firms in order to induce optimal investment but all rents are transferred to the regulatory body.

Take the case of a tax on output where τ is the tax level set by the regulator assuming fixed wage labor payments is implicitly defined by equation (1.11). If such a tax rate, τ, was constructed assuming fixed wage labor payments and used in an operating profit sharing remuneration regime, then the resulting equilibrium investment would be optimal if and only if the share is equal to the share of total costs from capital as in equation (1.15), the same condition which would lead to optimal fleet capacity in a property rights management regime. This result is not surprising; optimal taxes align private costs with social costs in precisely the same way as internalizing social costs via property rights management. As before, though, there is no guarantee that this be true in general, in which case investment is too great or too little.

Alternatively, an operating profit sharing remuneration structure in conjunction with a fee on capital constructed under a fixed wage assumption as in (1.12) will never lead to optimal industry capacity unless labor receives no share ($x = 1$).[16] If labor earns no share then there will always be overinvestment if a renewable resource is regulated with naively constructed taxes on capital if labor is remunerated as a share of operating profit. However, if labor earns no share then the remuneration constraint clearly binds. When the remuneration constraint binds, there is a unique level for which investment is optimal and maximum resource rents are captured by the regulator. The proof of this result is similar to that in proposition 3 and is not included here.

The combination of revenue sharing arrangements and price instruments leads to similar conclusions as those of operating profit share arrangements and price instruments. In fact, a tax on output constructed under the fixed wage assumption will lead to optimal investment in the presence of revenue sharing arrangements if capital owners' share is

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[16] The result follows after letting equation (1.12) implicitly define the fee Φ and solving for the operating profit share, x, which gives optimal investment.

equal to the share or total costs from capital as is equation (1.15). This is the same condition which would lead to optimal fleet capacity in a property rights management regime and a tax on output in the presence of operating profit sharing. Revenue sharing in conjunction with a capital fee will never lead to optimal industry capacity unless labor receives no share ($x = 1$) as with an output tax. In the case of output taxes, optimal investment occurs if capital owners earn the proportion of income that is due to their contribution to the production process because labor shares the relative change in the output price. In the case of capital fees, labor does not share the cost of the increased capital costs but the benefits from increased investment continue to accrue to them. The reason for the similarities between revenue sharing and operating profit sharing is that in both cases labor does not split capital costs. When labor shares the cost of capital with capital owners, as in full profit sharing remuneration regimes, similarities quickly break down.

The combination of full profit sharing remuneration agreements and price instruments (either taxes on output or capital) lead to the most stark investment inefficiencies. As stated above, optimal taxes change prices so that at the optimal industry size, the expected profit of an entering firm is zero. If labor is paid with a fixed wage, taxes will not affect the income of labor that stays in the industry. If labor shares revenues less operating costs and capital costs, though, a price instrument would imply that labor earns no income at the optimal fleet capacity.

Consider the firm's incentives with a tax derived under the fixed wage assumption in equation (1.11):

$$x((1-\tau)p-c)\left[\left[\int_{Q_{min}}^{kN^{\tau}} \frac{Q}{N^{tau}} f(Q)d(Q) + k(1-F(kN^{\tau}))\right] - (d+r)K\right] = 0 \qquad (1.24)$$

Equation 24 can be interpreted to mean that firms enter until there is no expected profit from doing so under the new price structure. Setting $N^{tau} = N^{*}$ implies that share level x which gives optimal fleet capacity is $x = 0$. A share level of $x = 0$ implies that capital owners earn no income. As a result, there is a multiplicity of equilibria: firms earn no income for any level of investment. Therefore, if $x = 0$, labor's remuneration constraint determines investment levels and the remuneration constraint binds at optimal fleet capacity. If $x > 0$ then the remuneration constraint determines the investment level and capacity is always below the optimal level.[17] The same intuition applies for fees on

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[17] Intuitively, labor must earn 100% of income in a full profit sharing scheme under price instrument

capital derived under the assumption of fixed wage payments in equation (1.12). As a result, we conclude that price instruments constructed under a fixed wage assumption will always lead to the remuneration constraint being binding and lead to underinvestment in all non-trivial cases.

Table 1 shows the findings in this section. Generally, any linear share economy applied to renewable resources scale wage pay regimes can lead to over- or under-investment in a property right management regime. If price instruments are used, then full profit sharing will inevitably lead to underinvestment, but other share remuneration structures can lead to over- or under-investment. It must be the case that if labor is remunerated via operating profit sharing then they must earn some fraction of resource rents at the optimal industry investment level.

Table 1.1: Industry Capacity Relative to Optimum

Remuneration Regime	Management Regime		
	Property Rights	Output Tax	Capital Tax
Scale Wage	Over/Under	Over/Under	Over/Under
Op. Profit Share	Over/Under	Over/Under	Over/Under
Full Profit Share	Over/Under	Under	Under

1.3.4 Variable Unit Profits

Profit per unit of output in renewable resource harvests is usually thought to vary with the size of the renewable resource stock. Intuitively, if the resource stock is very large, then the cost of harvesting a given amount of the resource might be relatively smaller than if the resource stock size was very small. The Hannesson (2000) model extended here assumes that unit of output profits are constant across all harvest sizes. If the target harvest size chosen by the resource regulator is indicative of the stock size, as almost always the case in well managed renewable resource industries, then it is important to understand how relaxing the constant unit profit assumption affects investment dynamics addressed in this paper.

The most developed model in renewable resource economics in which profits are responsive to resource stock size is in fisheries. In fisheries, the classical Gordon-Schaefer

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regulation because price instruments rotate the industry's marginal benefit or marginal cost curves. However, share remuneration also rotates the industry's marginal benefit curve. When labor earns all income, these two effects offset each other leading to optimal fleet capacity.

model specifies that total fishing profits are $\pi(X) = PqEX^{\alpha} - cE$ where P is price, q is the catchability coefficient, a measure of overall efficiency, E is a metric for fishing effort, X is the stock size of the target species and α is the stock elasticity, which indicates how sensitive costs are to the size of the target species. For a given level of fishing effort and stock size, a species with a larger α produces higher unit profits than if α is low within the permissable range, $\alpha \in [0,1]$. The Gordon-Schaefer model embeds the constant unit profit model when $\alpha = 0$.

In the Gordon-Schaefer model, profit per unit effort is $\frac{\pi(X)}{E} = PqX^{\alpha} - c$. The first and second derivative of unit profits are

$$\frac{\partial \frac{\pi(X)}{E}}{\partial X} = \alpha PqX^{\alpha-1} \qquad \frac{\partial^2 \frac{\pi(X)}{E}}{\partial X^2} = (\alpha - 1)\alpha PqX^{\alpha-2}.$$

By inspection, the first derivative of unit profits is positive and the second derivative is negative. The function $\alpha(1-\alpha)$ is zero if $\alpha = 1$ or $\alpha = 0$ and is largest in magnitude when $\alpha = .5$.

Now consider a generalization of the Hannesson (2000) model in which unit profits are a function of stock size and there is a monotonic function mapping stock size X to realized TAC Q. Without loss of generality, unit profits can be written as $\pi(Q)$ where $\pi'(Q) > 0$ and $\pi''(Q) < 0$, as implied by the Gordon-Schaefer model. The following two equations show the augmented total expected value from resource harvest in the model with variable unit profit under exogenous wage payments and operating profit sharing:

$$EV = \left[\int_{Q_{min}}^{kN} \pi(Q) N \frac{Q}{N} f(Q) d(Q) + kN(1 - F(kN))\pi(kN)\right] - (d+r)KN - wN \tag{1.25}$$

$$EV = x\left[\int_{Q_{min}}^{kN} \pi(Q) N \frac{Q}{N} f(Q) d(Q) + kN(1 - F(kN))\pi(kN)\right] - (d+r)KN \tag{1.26}$$

As before, the equations differ only by the exclusion of the exogenous wage in equation and inclusion of owner share level x in equation (1.26). A social planner maximizes expected rents by maximizing equations

$$[\underbrace{\pi(kN^*)}_{(P-c)} + \pi'(kN^*)kN^*]k(1 - F(kN^*)) = (d+r)K + w \tag{1.27}$$

$$x[\underbrace{\pi(kN^*)}_{(P-c)} + \pi'(kN^*)kN^*]k(1 - F(kN^*)) = (d+r)K \tag{1.28}$$

In both first order conditions, the constant unit profits are embedded in the more general case. As before, the proper interpretation of the equilibrium conditions is that the marginal benefit of adding another vessel must be equal to the marginal cost. The difference between the FOCs in equations (1.27) and (1.28) and the FOCs with constant unit profits is the inclusion of an additional term which embodies the change in unit profits when harvesting at industry capacity as industry capacity increases, $\pi'(kN^*)kN^*$. If there is a significant increase in unit profits when stock sizes are large, then there is an additional benefit to adding capacity because the additional capacity can recover more of the relatively higher rents.[18]

As in the constant unit profit model, in order for profit sharing to give the socially optimal level of investment observed in the exogenous wage payments case, expected crew remuneration at when the industry is harvesting at capacity must equal the opportunity wage of the crew:

$$(1-x)[\pi(kN^*) + \pi'(kN^*)kN^*]k(1-F(kN^*)) = w. \tag{1.29}$$

As in the case of constant unit profits, optimality implies that the crew earns resource rents at optimum capacity. Further, deviations from this share level lead to suboptimal investment levels.

The more general model of unit profits implies that deviations from the share level x^* leading to optimal industry capacity can cause either greater or smaller deviations from optimal fleet capacity relative to the constant unit profit case. To see this, consider the equilibrium condition in operating profit remuneration, equation (1.28). Dividing both sides by the share level which leads to optimal capacity, x^*, gives

$$\pi(kN^*) + \pi'(kN^*)kN^*k(1-F(kN^*)) = \frac{(d+r)K}{x^*}. \tag{1.30}$$

Now consider a deviation away from x^* to $\underline{\mathrm{x}} < x_*$. There exists a suboptimal industry size $\underline{\mathrm{N}}$ implied by $\underline{\mathrm{x}}$. By taking the derivative of the left hand side of equation (1.30) with respect to N, we can compare how the more general specification affects the size of any potential investment inefficiency.

The derivative of the left hand side of equation (1.30) can be written as

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[18] One problem of the modeling approach is that if unit profits vary with stock size, unit profits increase for all resource stocks corresponding with a harvest limit larger than capacity. Put another way, $\pi(kN)$ is not constant $(1-F(kN))$ percent of the time. This doesn't affect comparing the unit of effort wage remuneration with share remuneration within the model, though.

$$- k^2 f(kN)\pi(kN) + k^2 \left[(1 - F(kN))(2\pi'(kN) - kN\pi''(kN)) - f(kN)kN\pi'(kN)\right]. \tag{1.31}$$

First note that the term outside the bracket on the left corresponds to the constant unit profits case and is negative. Negativity of this term implies that as the share retained by owners falls relative to its optimum (x decreases) and the right hand side of (1.30) increases, investment levels N must fall. This is precisely what is shown in Proposition 1 and in the simulations.

The contents of the bracketed term is contributed by the more general specification of variable unit of effort profits. If the term is zero, then there is no difference in the rate of investment inefficiency caused by deviations from the share level leading to optimal capacity between the extended Hannesson (2000) model and the model presented here. When the content of the bracketed term is negative it means that a given fall in N leads to a more dramatic increase in the left hand side term in equation (1.30). In this case, the investment inefficiency is less severe than it would be in the case of constant unit profits. When the content of the bracketed term is positive, it means that a given fall in N leads to a less dramatic increase in the left hand side term in equation (1.30) and the investment inefficiency is more severe.

The key to determining the sign of the contents of the bracket term in (1.31) is the middle component $-kN\pi''(kN))$. As shown above, the Gordon-Schaefer model implies $\pi''(kN) < 0$. Further, if the stock elasticity is near the center of the permissable range, $\alpha = .5$, then the magnitude of the term is large and if the stock elasticity is near the bounds of the permissable range, $\alpha = \{0, 1\}$, then the magnitude of the term is small. As such, we would expect the inefficiencies caused by share remuneration to be largest for species with stock elasticities in the middle of the permissable range as the middle term in (1.31) becomes larger.

Note that nothing in the model prevents the entire term (1.31) from being positive. If the term were positive, when levels that are too low would lead to overcapacity, which is the opposite implication of the extended Hannesson (2000). The expression in (1.31) will be positive if changes in unit profits at stock levels associated with large catch limits are larger that levels of unit profits at those same stock levels. While this is a possibility in the model, it is highly unlikely in practice.

1.4 Simulations

This section shows how share remuneration can affect investment in renewable resource industries for all management regime introduced in the previous section. The simulations show the size of the economic inefficiencies caused by share remuneration has a particular set of parameters.

In the simulations below, we follow Hannesson (2000) in assuming the following functional forms:

- $Q \sim U[Q_{min}, Q_{max}]$
- $Q_{min} = 0$ and $Q_{max} = 100$
- $p = 1$, $d = .1$, $r = .05$, $w = .25$, $K = 1$ and $k = 1$

Given these functional forms and parameter values the remuneration models presented above will be analyzed with respect to the different natural resource management regimes. Excluding the efficiency wage remuneration model, there are nine possible permutations of remuneration and management strategy in addition to the social planner's solution where labor is paid their opportunity cost, w.

While this simulation is applicable for investment in agricultural development, production capacity in forestry or investment in fisheries, consider for concreteness the example of fleet capacity in a fishery. The problem of over-capacity in fishing fleets is well documented in open-access fisheries. This section shows how any linear share economy can affect fleet capacity in the different management regimes presented in the previous section. In this case, total production capacity, kN, can be thought of as fleet capacity N.

Figures 1, 2 and 3 show the results from simulating fleet capacity and expected crew remuneration on three different remuneration regimes and three regulatory regimes designed when assuming fixed wage payments. In each case, the figures also show the optimal equilibrium fleet capacity reached in the case of parametric wage structure as a baseline. Each combination of share remuneration and regulatory regime was selected to show a general characteristic that is present in each of the nine combinations simulated. Full results for all 9 combinations are shown in Table 1 above.

Figure 1 combines ITQ management with operating profit sharing. This is the share remuneration and regulatory structure in place in the halibut and sablefish fisheries

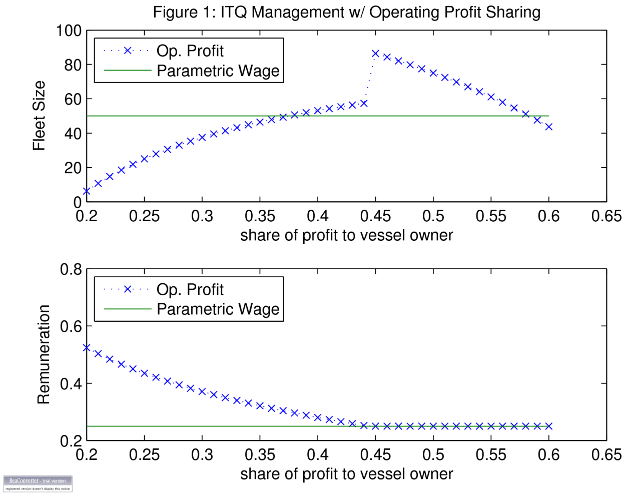

Figure 1.1: Capacity Under Property Rights Management with Operating Profit Sharing Remuneration as a Function of Percent x Paid to Owner

in Alaska. Moving from left to right on the x axis, a larger share of operating profits accrues to the owner. In this case, potential vessel owners are constrained by paying the crew their opportunity cost of labor. As such, for each incremental increase in the share of operating profits accruing to the vessel owner, the fleet size increases as long as the remuneration constraint does not bind. The reason for the increasing production capacity is that while that marginal cost of adding another boat is fixed at the rental cost of capital, the marginal benefit of adding another vessel is changing. The level of operating profits accruing to the quota owner rises as their share rises. As a result, as owners' share increases, more vessels will enter the fishery until the marginal vessel drives per vessel profits back to the marginal cost of investment. This result is true so long as the remuneration constraint doesn't bind.

The discontinuity in figure 1 occurs due to the labor's participation constraint binding. When the expected remuneration constraint binds, labor's expected remuneration requirement dictates the level of investment as opposed to the management regime. Because we consider only linear share remuneration, this model does not allow firms to offer a fixed wage component to offset the incompatibility property right dictated equilibrium and labor force participation. Over the region where fleet capacity discretely jumps in Figure 1 due to the remuneration constraint being binding, a non-linear profit sharing agreement could be reached that guarantees labor their opportunity wage in expectation. In this case, though, capital owners would in effect be sharing a percentage

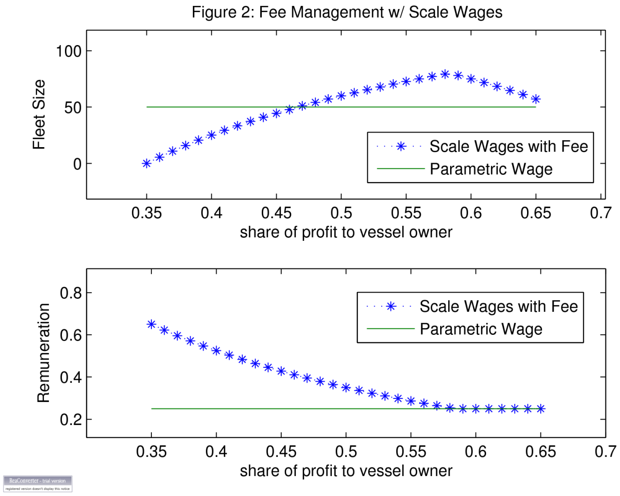

Figure 1.2: Capacity Under Capital Tax Management with Revenue Sharing Remuneration as a Function of Percent x Paid to Owner

of their resource rents it with labor to make the remuneration guarantee, thus moving back to, effectively, a higher labor share.[19]

Clearly, there are significant inefficiencies in natural resource management that result from the share economy in the case where the labor input payments bind. The reason for the significance of the jump is that the crew's executed remuneration doesn't account for the physical capital payments yet it fully accounts for the remuneration which occurs over the entire range possible TACs $[Q_{min}, Q_{max}]$. Also, as the owners' share increases beyond the level after which the remuneration constraint binds, production capacity begins to fall to compensate labor for decreased percentage share with increased per vessel revenue.

Finally, Figure 1 shows that the fleet capacity may be either below or above the optimal level. Over-investment would occur if firms' share is greater than the capital cost share, $x > \frac{(d+r)k}{(d+r)k+w}$, and labor's participation constraint holds, $E[M|x] \geq x$. Since labor earns resource rents at optimal fleet capacity, there is always a range over which these conditions are met. Labor earning rents at optimal industry capacity due to the share structure drives this result.

Figure 2 shows the inefficiencies associated with setting a naive tax on capital in the presence of scale wages.[20] With respect to fisheries, a capital tax may be thought of

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[19] To the author' knowledge, non-linear labor remuneration agreements are much less common than fully linear share agreements.

[20] Note that scale wages with ITQ management replicates the simulations in Hannesson (2000)

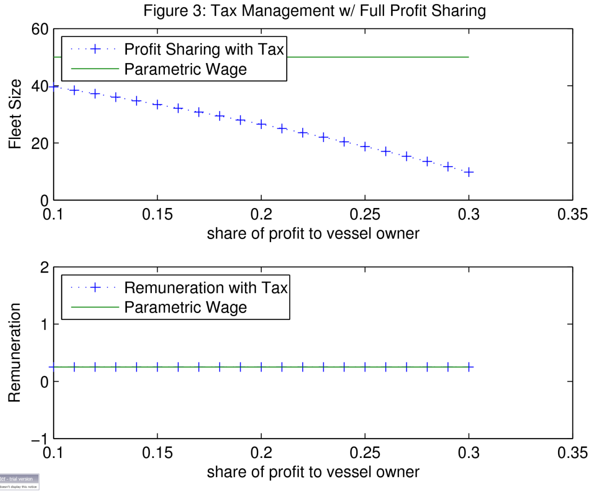

Figure 1.3: Capacity Under Output Tax Management with Full Profit Sharing Remuneration as a Function of Percent x Paid to Owner

as a yearly licensing fee on fishing vessels. A naive regulator constructs the capital tax by assuming fixed wage payments and choosing the tax so as to set industry economic profits equal to zero at the optimal fleet capacity. Scale wages are unique in that the remuneration structure doesn't have the crew directly sharing any of the regulatory costs with the vessel owner. This implies that the fleet size increases with the share accruing to the vessel owner as fishing becomes more individually profitable until the point where the vessel owner is constrained by the crew's remuneration constraint. When the expected remuneration falls below the opportunity wage of the crew, vessels begin to exit (as with the case above) in order to drive up individual vessels revenues to be shared with labor.

Figure 3 shows perhaps the most theoretically interesting combination of regulatory regime and remuneration regime: full profit sharing and output taxes. With respect to fisheries, a tax on output can be implemented as a landings tax. An optimal tax is derived by assuming an exogenous wage and setting expected industry profits to zero at the optimal fleet capacity by taxing the price received by firms for their output. Under full profit sharing, though, the vessel owner receives a certain percentage of the total profit. Further, the crew must receive at least their opportunity wage. Therefore, if any of a vessel's total profit accrues to the vessel owner under a landings tax regime (or a tax on capital regulatory regime) the crew will receive less than their opportunity wage. The result is that a landings tax will leave the owner with zero economic profit which is exactly what the original goal of the policy was. Thus, a landings tax in a full profit sharing regime where the vessel owner earns a positive portion of the profit will inevitably lead to below optimal fleet capacity. A landings tax will reduce fleet capacity over what it had been under open access. A similar result holds for licensing fees and full profit sharing. The implications for full profit sharing in renewable resource industries are that price instruments of any kind lead to under-investment.

We now show simulation results for an operating profit sharing remuneration structure when there are effort feedbacks effects. Two different functions relating cost and effort are assumed and integrated in the model presented above:

- 1) $c(e) = 1 - \frac{e^{1-\gamma}}{1-\gamma}$
- 2) $c(e) = exp(-\gamma e)$
- $g(e) = e$
- $f(Q) = \frac{1}{Q_{max} - Q_{min}}$
- $F(Q) = \frac{Q - Q_{min}}{Q_{max} - Q_{min}}$
- $Q_{min} = 0$ and $Q_{max} = 100$

These functional forms were chosen to show the sensitivity of the simulation results to the relative curvature of the cost function. Cost specification 1 has decreasing absolute curvature as defined by Arrow-Pratt, γ/e, and specification 2 has constant absolute curvature, γ. The implication is that in specification 1, costs are less sensitive to effort at high levels than low levels. Simulations were performed so as to evaluate different levels of the operating profit share x and different measures of cost function curvature. Figure 4 shows how fleet size varies with both x and γ in the model of scale wages with feedback effects with cost specification 1. Figure 5 shows the same graph using cost specification 2.

Figure 4 shows that for a given γ, a measure of responsiveness of cost with respect to effort, the number of boats in the fleet is essentially constant across different crew shares. Whereas excluding effort feedbacks implies fleet capacity is increasing in the owners' revenue share when the remuneration constraint doesn't bind, including effort feedbacks that may imply that fleet capacity is not increasing in owners' revenue share on this region. The reason is the decision by the crew to trade off between income and effort. The implication is that if the crew's expected remuneration is low, they will shirk

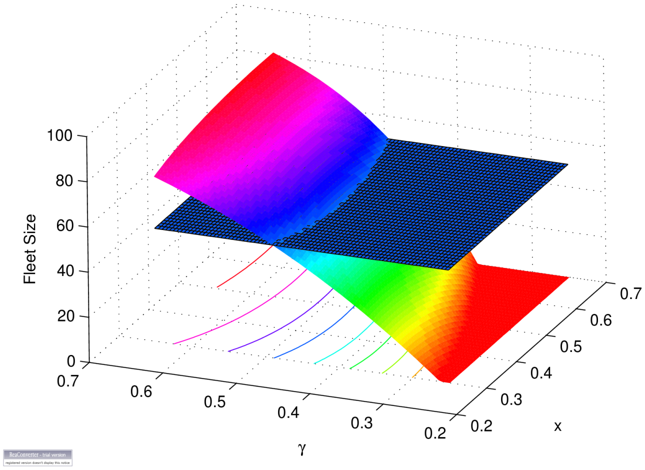

Figure 1.4: Investment under operating profit remuneration and ITQ management with feedback effects under cost function 1. Plane is set at 50, the fleet size under optimal management.

and reduce the potential profit to be received by the quota owner because the unit costs of fishing are now relatively higher. Further, additional boats will decrease the average share of profits for each pre-existing crew. This externality imposed on the remuneration of all crews by newly introduced vessels reduces the incentive to invest since additional vessels will decrease effort and increase unit costs via lower expected remuneration for all levels of effort.

Figure 5 shows that while feedbacks can potentially temper the distortion caused by profit sharing in renewable resource production processes, it can also exacerbate them. If the cost function exhibits constant relative curvature, then the resulting inefficiency from the share economy in renewable resources could be made worse. It is important to note that it makes drawing industry-specific conclusions about profit sharing an empirical question.

It is apparent in these figures that fleet size is increasing in the elasticity of cost with respect to effort. This makes intuitive sense since the marginal benefit of effort to workers is greater when effort is increased. As such, lower unit costs lead to increased value of resource extraction. In sum, over- or under-capacity is tempered by effort feedbacks if the cost function exhibits decreasing relative curvature and is potentially exacerbated if the cost function exhibits constant relative curvature.

In a property rights management with fixed wage payments, as the wage rate

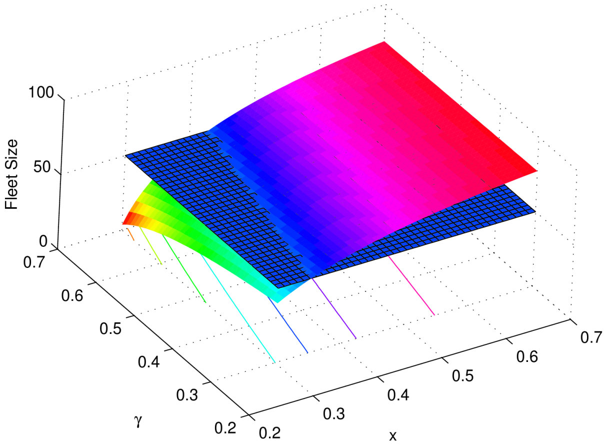

Figure 1.5: Investment under operating profit remuneration and ITQ management with feedback effects under cost function 2. Plane is set at 50, the fleet size under optimal management.

falls, investment will rise. We find the opposite result here: if labor is to be paid a low profit share, then there is less of an incentive to invest since little effort is expended and unit costs are high. When the labor is paid a higher share, there is more effort, increased industry profits, and as a result, more investment.

1.5 Optimal Management Accounting for Remuneration Regime

It is possible to account for realistic remuneration regimes in fishery management and reach a first best solution. Take, for example, the case of ITQs and operating profit sharing. Operating profit sharing is by far the most common remuneration regime in fisheries. As stated above 98% of the Pacific coast troll fleet use some form of operating profit sharing. An ITQ regime will lead to too much or too little fleet capacity due to a vessel owner not receiving the full benefit from holding an ITQ, as they must share some of the resource rents with the crew. One way to ensure optimal investment levels is to use a hybrid regulatory policy which incorporates both tax and quantity regulation. Pizer (2002) has shown that there may be benefits to using hybrid regulatory policies for climate change in the case of price uncertainty. Smith (2009) shows that high grading behavior in fisheries can be eliminated by using a tax in conjunction with ITQs.

Hannesson (2007) shows that inefficient fleet capacity caused by revenue sharing in ITQ managed fisheries cannot be remedied with taxes on quota holdings but may be remedied by appropriate pairings of taxes and revenue sharing levels. The results here are different from Hannesson (2007) in that they are robust to all pairings of regulatory regime and share structures and account for labor's remuneration constraint. The results presented here show that using taxes on output or capital in conjunction with property rights renewable resource management can lead to first best investment level.

We have seen that operating profit remuneration with property rights management can lead to over- or under-capacity in renewable resource industries. The equilibrium for property right management is given by setting the cost of adding another capital unit to the expected marginal revenue accruing to an owner of providing the investment. Under operating profit sharing, equilibrium is defined by

$$x(p-c)k(1-F(kN)) = (d+r)K. \tag{1.32}$$

This will by no means lead to the optimal investment levels. If it does then labor must earn a share of the economic rents as shown above.

Consider an alternative management structure that combines a vessel licensing fee (or subsidy) with property rights management. Assume the regulator derives the first best level of investment N^* assuming that labor earns its opportunity wage. All that is left is to solve for the capital tax Φ which gives the optimal N^* as the equilibrium to the augmented property rights regime, ensuring that labor is paid at least the opportunity wage in expectation. This amounts to implicitly solving the following equation for a capital tax- $\Phi(N^*)$:

$$\begin{aligned} x(p-c)k(1-F(kN^*)) &= (d+r+\Phi(N^*))K && (1.33)\\ \text{s.t.} \quad (1-x)(p-c)&\left[\int_{Q_{min}}^{kN^*} \frac{Q}{N^*} f(Q)d(Q) + k(1-F(kN^*))\right] \\ &- (d+r+\Phi(N^*)) \geq w && (1.34)\end{aligned}$$

In order to show how the optimal capital tax varies over different share levels, consider again the example of ITQ management in fisheries. In this simulation, an optimal capital tax is constructed in conjunction with ITQ management and operating profit sharing remuneration so that fleet capacity N is at the social planners level. Assume the same parameters as before.

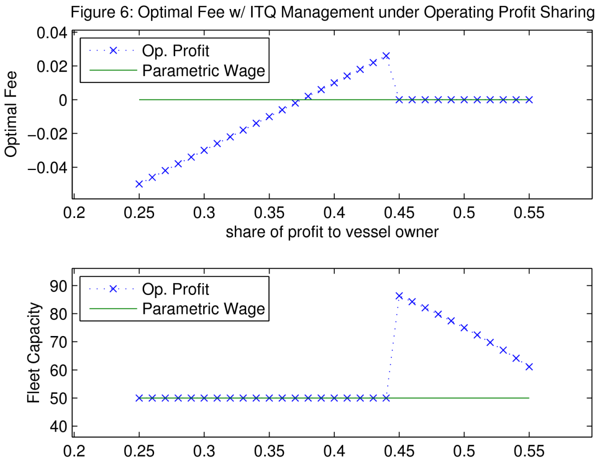

Figure 1.6: Optimal capital tax under ITQ management with operating profit sharing as a function of share x paid to vessel owner.

Figure 6 shows the schedule of optimal capital taxes for different levels of owner's profit share in the same simulated fishery used above. In this simulation, while capacity is not constrained by crew remuneration requirements, the fleet should be subsidized at some fixed amount per vessel in order to ensure optimal fleet capacity. The degree of the subsidy or tax on vessels or landings will be subject to the traits of a particular fishery as shown in the calibrated model below. Note that once the owner's share exceeds 45% in this particular simulation, the optimal fee is zero. The reason for this result is that at this point, the expected remuneration condition binds determining fleet capacity and ITQ management no longer dictates capacity unless a non-linear class of remuneration structures are considered.

Constructing optimal output or capital taxes accounting for realistic remuneration regimes is relatively simple in the absence of property rights management. Hannesson (2007) shows that in a fishery, a tax on landings can lead to optimal fleet capacity if the crew is paid as a share of total revenue, but that a tax on quota holdings would serve no purpose other than to transfer rents from industry to regulator and this result be can replicated here. The optimal tax or fee is found in a similar way as in the ITQ case above, but the equilibrium condition is slightly different since a price instrument is used as opposed to an ITQ which regulates quantity:

$$
\begin{aligned}
E[V] &= x((1-\tilde{\tau})(p-c)\left[\int_{Q_{min}}^{kN^*} \frac{Q}{N^*} f(Q)d(Q) + k(1-F(kN^*))\right] \\
&- (d+r+\tilde{\Phi})K = 0 \qquad (1.35) \\
\text{s.t.} \quad & E[M; x, \tilde{\tau}, \tilde{\Phi}] \geq w \qquad (1.36)
\end{aligned}
$$

This expression suppresses the precise remuneration regime. It may be noted that as long as the remuneration regime is accounted for explicitly, then it is possible to find a first best policy instrument via either a tax on output $\tilde{\tau}$ or capital $\tilde{\Phi}$.[21] This amounts to the regulator correctly specifying their objective function.

1.6 Empirical Example and Calibration Exercise

In this section, empirical evidence for the implications of the theoretical model is given using data from the Alaskan halibut and sablefish fishery. The theoretical model is then calibrated using data from the North Pacific albacore tuna fishery and an optimal policy is developed based on the calibrated parameters. In both cases, the predictions of the theoretical model appear to be present and significant.

Before 1995, both the sablefish and halibut fisheries in Alaska were managed by industry level total allowable catch limits (TACs). Any licensed vessel could enter and fish until the sum of all vessels' catch reached the fishery's catch limit.[22] From 1960-1994, the value of the annual sablefish and halibut catch ranged from roughly \$100-250 million and from 1979-1994 the fleet exceeded catch limits by an average of roughly 5% (CGER 1999).

In 1995, the regulatory body overseeing the two fisheries implemented tradeable property rights over both the Alaskan halibut and sablefish longline fisheries. Due to congruent season times, fishing gear and fishing techniques, all owners of halibut quota also own sablefish quota. Operating profit sharing was the remuneration scheme before and after the ITQ management implementation (Casey et. al. 1995). In this fishery, quota shares are transferable but the total amount of landings associated with a quota share fluctuates in direct proportion to the quota share as in this paper's theoretical model.

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[21] It is worth noting that taxes on quota holdings can be effective in either operating or full profit sharing remuneration regimes.

[22] At the end of the season, it was common during this time for the regulator to place effort controls on the fishery to avoid passing the TAC.

The model presented here implies that operating profit sharing in a property rights management regime such as ITQs in fisheries can lead to either over- or under-capacity of the fishing fleet relative to the social planner's optimum. If this particular fishery suffered from over-investment then regardless of TAC, we might expect the entire TAC to be caught in every period. Alternatively, if the fishery were under-capitalized, we would expect to observe less than 100% of the TAC taken in on average and that in high TAC years we observe excessively low takes.

Data was collected for TAC levels and landings levels for both sablefish and halibut from 1991-2009 by NFMS. The data from 1991-1994 is included to show the dramatic over-harvesting that occured during that time period. Data from the 1980s was not included, as there was significant fishing pressure from other nations such as Taiwan and Russia during that time period. Summary statistics are presented in Table 2, organized by years.

Table 1.2: Summary Statistics for Alaskan Halibut and Sablefish Fisheries by Season: 1991-2009

Species	Data Type	1995-2009 Average	St. Dev.	pre-1995 average
Sablefish	TAC Weight (tons)	32,600	4948	47,200
	Catch Weight (tons)	29,700	4264	47,400
	Catch/TAC	.912	.02	1
Halibut	TAC Weight (tons)	52,000	7500	47,100
	Catch Weight (tons)	50,100	7,920	48,400
	Catch/TAC	.96	.03	1.03

NOTE: Data from National Marine Fisheries Service Alaska Regional Office

It is immediate from the data that under-capacity might be an issue in this fishery.[23] The halibut fishery was larger over this time frame and fisherman earned a price premium on halibut.[24] As such, it is reasonable to see that the percent take of the TAC is significantly lower for sablefish than for halibut, as fishermen substitute effort toward sablefish only when marginally profitable to do so.

If under-capacity is an issue in this fishery, the econometrician would observe

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[23] Redstone (2007) found that ITQ managed fisheries generally don't catch the entire TAC in a given year but are agnostic as to why.

[24] Matulich and Clark (2003) found a 35% price premium on halibut in 1999-2000. Over this time period, the whole sale price of sablefish was \$ 3.01/pound versus \$ 4.15/pound for halibut.

that in years where the TAC for halibut is high, the percent of TAC for sablefish taken would be low, given the price premium earned by fishermen on halibut. Table 3 presents the results of three regression specifications that test whether this is observed in the data. In each specification, the dummy variables are used to control for data before the adoption of property rights management in 1995 and the first year after implementing ITQ management was controlled for to account for the transition to a new management regime. In every specification, these controls are highly significant and not reported. The coefficient estimates that are reported are only those on post-ITQ management explanatory variables.

In specification 1 the dependent variable is the sum of sablefish and halibut catches in a given year divided by the sum of TAC for sablefish and halibut allocated in a given year. The explanatory variable in specification 1 is the sum of TAC for sablefish and halibut in a given year divided by the maximum sum of TAC for sablefish and halibut over all years. As the total TAC in the fishery approaches its maximum, if the fleet is capacity constrained, then the percent of the TAC taken should fall since both species are taken by the fleet. The coefficient on the explanatory variable has the predicted sign but it is not significant. Note that since the data is summed by year in specification one, there are only 16 degrees of freedom in this regression.

In specifications 2 and 3 the data are disaggregated by species. Each specification has the following reduced form, with specification three including the additional bracketed explanatory variable.

$$\begin{aligned} \frac{catch_{it}}{TAC_{it}} &= \alpha + \underline{D}'\underline{\delta} + \frac{TAC_{halibut,t}}{max(TAC_{halibut})}\beta_1 \\ &+ \left[1\left(i = sablefish\right) \cdot \frac{TAC_{halibut,t}}{max(TAC_{halibut})}\beta_2\right] + \epsilon_{it}. \end{aligned} \tag{1.37}$$

In both specifications, the vector $\underline{D}$ represents various controls for the adoption of a new management regime. In specification two, the coefficient on the percent of the maximum halibut TAC is the coefficient of interest. If a fleet suffers capacity constraints then we would expect that as the TAC of the primary species is large relative to other years, then the realized catch is small as a percentage of that TAC. Specification three includes the interaction term for sablefish and the ratio of the current period TAC for halibut to the maximum TAC for halibut.

Neither variable of interest in specification 1 or 2 are significant, but the statistical

Table 1.3: Regression Results for TAC and Catch in Alaskan Halibut and Sablefish Fishery

Explanatory Variable	Specification		
	(1)	(2)	(3)
year one	-.063***	-.06**	-.059***
	(.002)	(.029)	(.019)
% max total TAC	-.024	-	-
	(.048)	-	-
% max Halibut TAC	-	-.008	.06*
	-	(.033)	(.031)
Sablefish x % max Halibut TAC	-	-	-.137***
	-	-	(.054)
intercept	.967**	.969***	.911***
	(.041)	(.03)	(.028)
r^2	.56	.60	.65
n	19	38	38

This data was taken from the Alaska Regional Fisheries office of the NOAA.

*** = significant at 1%, ** = significant at 5%, 1 = significant at 10%.

Robust standard errors are used.

significance of the coefficient on the added explanatory variable in specification 3 is instructive. The interpretation of the coefficient's value, -.137, is that if the halibut fishery is allocated its maximum TAC, then the model predicts that the sablefish fishery will catch 1.37% less of their TAC allocated in that season than they would have if the halibut fishery was allocated 90% of their maximum TAC. Put another way, each 10% that the halibut TAC increases, the sablefish fishery catches 1.37% less of their allotment. Further, by adding this additional regressor, we see the intuitive result that the halibut catch significantly increases (at the 10% level) when the TAC for halibut increases. This result implies that fishermen target halibut over sablefish and that this fishery is indeed capacity constrained. These constraints lead to forgone economic rents, however, they also might lead to a larger resource stock.

Given that there is evidence of capacity constraints in a property rights managed fishery, the regulator needs to know the size of the inefficiency to develop a corrective policy. This section calibrates the model presented above using data from the albacore troll fishery off the west coast of the United States. This fishery remunerates labor as a share of operating profit. Currently, the troll fishery is open access but they are considering adopting ITQ management in order to increase rents. If the albacore fishery were to adopt ITQs as a management regime, then we would expect the number of vessels participating in the fishery to fall dramatically. This exercise uses data compiled from a variety of sources to calibrate the model. The goal of the calibration is to show the magnitude of the difference between the optimal fleet size which would result in the fixed wage case versus the expected fleet size under the observed operating profit share remuneration. Pacific albacore was chosen because the species has a relatively stable biomass, which gives a lower bound to the magnitude of the investment effect of the share economy in renewable natural resources.

The catch and biomass data are those used for the international resource stock assessments of North Pacific albacore and range from 1981 to 2006 (McDaniel, Crone, and Dorval 2006). Over this time period there was no formal limited entry agreement and this fishery can be thought of as open access. Vessel level panel data on costs is taken from surveys collected by the albacore industry from 1996-1999 (Squires et. al. 2003). Costs are divided into 2 groups: fixed costs and variable costs. Variable costs include both labor costs and other variable costs such as fuel and bait costs. According to the survey cost data, the crew's remuneration regime in this fishery is operating profit sharing. Fixed costs to vessels are paid by boat owners and variable costs like fuel and bait are shared with the crew.

A Leontief production function is assumed such that the crew's share of the variable cost is constant over time. This assumption could be called into question if relative prices lead to change in investment rates but for this simple calibration that concern is ignored. Further, there was some variation at the vessel level for the precise crew share, but that information is not available in the data set.

Table 5 shows summary statistics for costs in the US North Pacific Albacore fishery from 1996-1999. The crew's remuneration accounted for an average of 43.6% of the variable costs in this fishery between 1996 and 1999. Using Baa bond ratings for capital costs from Moody's as in Squires and Vestergaard (2009), variable costs account for, on average, 45.6% of total costs. A major simplification made here is that vessels are assumed to be uniform. For the calibration, we take 180 short tons to be the capacity of an individual vessel.[25] Note that operating profit in Table 3 is calculated before the

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[25] This level is assumed in order to match the days at sea data taken from Squires et. al. (2003). Anecdotal evidence from the American Albacore Fishing Association suggest that a large modern albacore vessel could have a capacity of nearly 300 short tons. One explanation for the low catch per vessel is not only competition due to open access but fisherman not exclusively targeting Albacore throughout

crew's share is removed.

Table 1.4: Cost Data from US South Pacific Albacore Troll Fishery, 1996-1999

Data Level	Category	Average	St. Dev.
Fleet Level	Number Vessels	866	214.8
	Days per Vessel	39	10.0
	Catch per Vessel (tons)	59.5	27.6
	Price Albacore (2001 USD/ton)	1,717.56	410.8
Vessel Level	Crew Remuneration	19,035 (194.40)	11,567
2001 USD/vessel	Other Variable Costs	24,608.97 (413.60)	14,460
(per ton)	Fixed Costs	52,008 (874.08)	4,613
	Total Costs	95,651.97 (1,607.60)	22,093
	Total Revenue	102,194.82 (1717.56)	56,123
	Operating Profit	77,585.85 (1303.96)	22,935
Ecological	Biomass	211,130	16,378
Metric Tons	Yield	13,915	2,829
	Ave. Yield/Biomass	.066	

NOTE: Data taken from Squires et. al. (2003), McDaniel et. al. (2006) and Squires and Vestergaard (2009)

Table 5 shows that the average vessel earned just positive accounting profits between 1996 and 1999 although the average vessel. This result is not unexpected given that this fishery was open access over this period. 27.8% of operating profit accrued to the crew.[26]

Stock assessments from McDaniel, Crone, and Dorval (2006) were fit to a normal distribution with a Shapiro-Wilk test for normality failing to reject the normality assumption. Parameters for potential US TAC allocations were taken from the highly migratory species fisheries management plan as ratified by the National Marine Fisheries Service in 2007 in order to give accurate values for ITQ management. Under the 2007 management plan, the US regional fishery takes roughly 16% of the TAC. The model is calibrated such that the Pacific albacore fishery continues to be sustainably harvested with the TAC taken to be the function of biomass estimates taken from the distribution

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the fishing season. Note that using a percentage difference from optimal fleet capacity can abstract from this parameter.

[26] It is important to note that fleet capacity for this fishery is not fixed over the time period in which the data were collected since tuna trollers can also be used in other fisheries in seasons that overlap with the albacore tuna fishery. Therefore we calibrate the model using cost and harvest data only for trollers that exclusively fished albacore over this period. This accounts for over 73% of the observed albacore catch. A different specification using all available data was also performed and yield even more pronounced results.

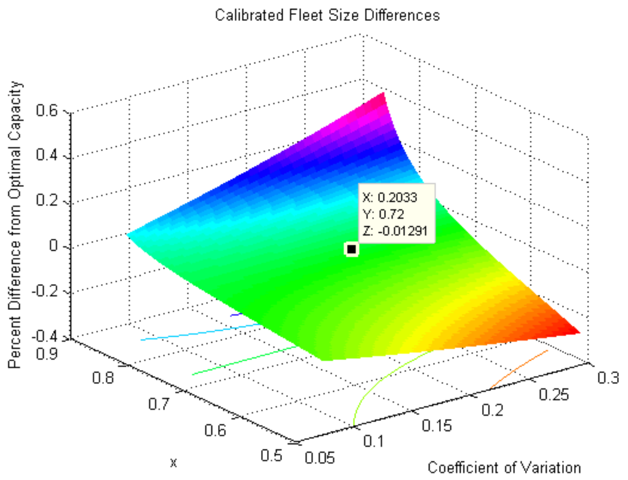

Figure 1.7: The Share Economy and US West Coast Albacore Calibration

described by the data.

Unit costs are primarily a function of fuel, damage to product, and bait. The component in variable unit costs associated with diesel fuel is conservatively parameterized at 60%. This price of diesel fuel was updated to reflect the average price from June 2008 to June 2009, normalized to 2001 US dollars. As such, we use unit costs of \$810 per ton rather than the \$414 per ton in the original survey data, although both specifications yield similar results. The model was then used to find the expected fleet size relative to the optimal fleet size. Optimal fleet size is derived by assuming that the wage rate observed in the data is the opportunity wage.

Figure 7 shows how fleet capacity in an operating profit regime varies relative to parametric wages over different levels of both owner's share and variation of the fish stock. Variation in stock is shown as the coefficient of variation ($\frac{\sigma}{\mu}$) of the distribution of the resource stock. The point highlighted on the graph shows the amount of under-capacity, almost 1.3%, that we would expect to see in this fishery due to the particular level of the coefficient of variation ($\frac{\sigma}{\mu}$=.21) and operating profit owner's share (x=.72) observed in the data. Proposition 1 implies that a share level of .732 would give first best fleet size. The figure shows that the size of the inefficiency is increasing with the amount of variation due to the share remuneration structure. As such, in renewable resource industries with more variable resource stocks, the size of the inefficiency would clearly be larger given these price levels. The reason that under-capacity is observed in this fishery is due to the price levels observed in the data. Given a different set of prices, ITQ management in this fishery could lead to over-investment. In order to address this under-capacity, the regulator could subsidize fishing activity. A yearly subsidy of roughly \$1681 per boat would be needed in the US south pacific albacore fishery to ensure first best investment levels due to the share remuneration structure.

Perhaps more interesting than the investment inefficiency in calibration is the level of remuneration the crew can expect from the share economy in conjunction with ITQ management. The calibration predicts that the crew earns almost twice their previous wage after ITQs are in place so long as the level of share structure does not change. The implications for the political economy of stake-holders in renewable resource industries is clear. In the case of fisheries, although the total quantity of labor employed in the fishery will fall if an ITQ management system is implemented, those who stay in the fishery are predicted to earn more than their opportunity wage.

1.7 Capacity Constraints and Renewable Resource Management

Profit sharing remuneration agreements between resource owners and labor in natural resource industries have been shown to lead to sub-optimal levels of investment in physical capital. Using an empirical example and a calibration exercise, the ITQ managed fisheries with profit sharing remuneration agreements are undercapitalized relative to the social planner's optimum. As a consequence, they also appear to be sub-optimally constrained in their harvesting practices. While the economic inefficiency that results from the share economy in renewable natural resource industries is undesirable from a resource rent perspective, constrained natural resource exploitation rates can result in ecological benefits of larger resource stock size and a more resilient resource stock.

To look at this issue, consider a stylized version of the Reed (1979) and Costello and Polasky (2008) models where the stock size of the renewable natural resource is x_t. In the model, the growth function is subject to an idiosyncratic multiplicative shock which creates a stochastic resource stock size. Between periods, the resource stock grows according to a concave surplus growth function $f(\cdot)$, and a multiplicative error term z_t, subject to a cumulative distribution function $\Phi(z)$ with mean one and support $[0, b]$ where b is finite:

$$x_{t+1} = z_t f(e_t) \text{ s.t. } e_t = x_t - h_t. \tag{1.38}$$

Here, e_t can be thought of as escapement and h_t the level of harvest in period t.

In the model, price is assumed to be some time invariant p and a unit cost function $c(x_t)$ is assumed to be decreasing and convex in x_t. Given this cost structure, there will be a stock level, defined as $\hat{x}_t$, for which within period marginal profits are driven to zero, or $p = c(\hat{x}_t)$. Define the level of stock size left by the myopic harvester who maximizes current period profits only as $\underline{x} = max(0, \hat{x}_t)$. We can then define the within period profit of harvesting from a starting stock size x down to $\underline{x}$ as[27]

$$Q(x) = p(x - \underline{x}) - \int_{\underline{x}}^{x} c(s)ds. \tag{1.39}$$

Given a constant discount factor, δ, we can write the stochastic dynamic programming summarizing the social planner's problem of maximizing resource rents as

$$V_t(x_t) = \max_{e_t} \left[Q(x_t) - Q(e_t)\right] + \delta E_t \left[V_{t+1}(x_{t+1})\right]. \tag{1.40}$$

Within this framework, Costello and Polasky (2008) shows equation (1.40) is a "state independent control problem" meaning that the optimal control is invariant to the value of the current state variable. Intuitively, this implies that the current stock size does not affect the level of stock the social planner wishes to allow be left to rebuild at the end of the harvest period. As such, optimal management is characterized by allowing some level of constant escapement, S, which maximizes expected rents.

A simple extension of the model is developed here in order to find the stock dynamic created under-investment, and capacity constraints in general, in renewable resource industries. Consider the same problem with the added constraint that industry capacity might not allow for full resource harvesting. If the industry harvesting capacity is represented by $\overline{h}$, the constraint is

$$\text{if } x_t - \overline{h} < 0, \; e_t \in [0, x_t] \; \text{ else } e_t \in [0, x_t - \overline{h}] \tag{1.41}$$

---

[27] Reed (1979) and Costello and Polasky (2008) do not consider the share remuneration structure. Wages and capital costs are subsumed into the unit cost function. As such, the within period profit function in the share economy may be written as $\tilde{Q}(x) = \kappa[p(x - \underline{x}) - \int_{\underline{x}}^{x} c(s)ds]$ where κ is less than one. If κ is constant over time, then including it in this particular modeling approach is trivial. As such, this term is left out in this section's exposition.

First consider how adding a capacity constraint like equation (1.41) affects a naive regulator who does not account for capacity constraint and continues with a constant escapement policy. Assume that the constant escapement level set by this regulator is e^* and that $f(e^*) - e^* < \overline{h} < bf(e^*) - e^*$. Not accounting for capacity constraints leads to a larger expected stock size in all future periods.

Proposition 4. *Non-trivial renewable natural resource harvesting constraints lead to a larger expected stock size in future periods if not accounted for.*

Proof. Rewrite the dynamic programming problem in equation 3 as

$$V_t(x_t) = \max_{e_t} \left[Q(x_t) - Q(e_t)\right] + \delta E_t \left[Q(x_{t+1}) - Q(e_{t+1})\right] + \delta^2 E_t \left[V_{t+2}(x_{t+2})\right]. \tag{1.42}$$

Assuming the continued use of the harvesting rule without capacity constraints, escapement is defined as

$$e_{t+1} = \begin{array}{ll} e^* & \text{if} \quad e^* \geq x_{t+1} - \overline{h} \\ x_{t+1} - \overline{h} & \text{if} \quad e^* < x_{t+1} - \overline{h} \end{array} \tag{1.43}$$

Note that escapement in period $t+1$ will be greater than 'naive' optimal escapement, e^*, due to capacity constraints whenever $e^* < x_{t+1} - \overline{h} = z_t f(e_t) - \overline{h}$. Therefore, period t expectations of escapement in period $t+1$ are given by

$$E_t(e_{t+1}|e_t = e^*) = f(e^*)\Phi\left(\frac{\overline{h}+e^*}{f(e^*)}\right) + \left(1 - \Phi\left(\frac{\overline{h}+e^*}{f(e^*)}\right)\right)\left[\int_{\frac{\overline{h}+e^*}{f(e^*)}}^{B} z d\Phi(z) f(e^*) - \overline{h}\right]. \tag{1.44}$$

Given that the growth function $f(\cdot)$ is concave and $\left(1 - \Phi\left(\frac{\overline{h}+e^*}{f(e^*)}\right)\right) > 0$, the expected stock size in period $t+2$ at time t is bigger in the presence of capacity constraints. The argument holds for all time periods since the growth function is time invariant. As a result, failure to account for renewable resource harvesting constraints leads to larger future expected stock sizes. *Q.E.D.*

If harvesting constraints bind, then the resource stock has a larger rebuilding stock which in turn leads to larger expected future resource stocks.

Another result that follows from the presence of capacity constraints is a change in the form of the escapement rule. Upon adding the capacity constraint the problem no longer exhibits “state independent control” in a Costello and Polasky (2008) sense, as the following lemma shows:

Lemma 1. *The presence of non-trivial capacity constraints as in equation* (1.41) *in conjunction with the maximization problem in equation* (1.40) *imply that equation* (1.40) *does not exhibit state independent control.*

Proof. Assuming an interior solution, in order for equation (1.40) to exhibit state independent control, the first order condition of equation 3 must be independent of x_t. The first order condition of equation (1.40) is

$$-Q'(e_t) + \delta E_t\left[\frac{\partial V_{t+1}(x_{t+1})}{\partial x_{t+1}}\frac{\partial x_{t+1}}{\partial e_t}\right] = 0 \tag{1.45}$$

To exhibit state independent control, we must show that equation (1.45) is independent of the stock variable x_t for interior solutions. By inspection, the constraint in equation (1.41) shows that $e_t < x_t - \overline{h}\ \forall\ t$. As such, the first term in equation (1.45) is a function x_t in the case that the capacity constraint may bind. *Q.E.D.*

The implications of state dependent control is that a constant escapement rule will, in general, no longer be optimal. This is a different result than found in Costello and Polasky (2008) and Reed (1979). Deriving the form of an optimal harvesting rule under a general remuneration share rule is beyond the scope of this paper, but clearly further research is needed.

1.8 Conclusion

The findings here suggest that share remuneration has important industry level implications in renewable resource industries. Share remuneration distorts the rate at which benefits accrue to firms thereby affecting the entry and exit decisions of firms so long as the exploitable resource stock is subject to some intertemporal variation. Policy instruments in place that were constructed under the assumption of fixed wage payments can lead to further economic inefficiencies. Further, there is no one-size-fits-all regulatory regime in a share economy as applied to renewable resources. Rather, a regulator needs to account for the specific type of remuneration structure that exists in the industry and property rights regulation need to be enforced in conjunction with taxes or subsidies to ensure first best outcomes, as noted in the revenue sharing case in ITQ fisheries by Hannesson (2007). In the calibration exercise using data from the North Pacific albacore tuna longline fishery a subsidy of roughly $1681/vessel would be needed to reach optimal investment levels if an ITQ management regime was implemented.

There could be ecological gains for the renewable resource stock attributable to share remuneration if it leads to under-investment. The ecological stability observed in ITQ managed fisheries as observed by Costello et. al. (2008) may be partially explained by the share remuneration structure observed in fisheries, as this leads to the inability of fleets under ITQ management to catch as much resource biomass as they otherwise would have under TAC management. This could lead to increased TACs in the future in fisheries. Similarly, piece rate remuneration in forestry and share-cropping in agriculture might lead to previously unexplored ecological benefits caused by under-investment. Because share remuneration can influence investment and lead to capacity constraints in any one period, constant resource biomass escapement is no longer necessarily optimal.

1.9 Appendix

1.9.1 Part A

Proposition 2:

In a operating profit sharing regime under property rights management, labor's expected remuneration is always above their opportunity wage regardless of the level of profit sharing at optimal fleet capacity as long as the resource harvest size varies and is dictated by a continuous and strictly monotonic cdf.

Proof: Equilibrium under property rights management in operating profit sharing remuneration is given by

$$x[(p-c)k(1-F(kN_{ITQ}^{op}))] = (d+r)K. \tag{1.46}$$

Algebraic manipulation of equation (1.46) gives

$$(p-c)k(1-F(kN_{ITQ}^{op})) - (p-c)(1-x)k(1-F(kN_{ITQ}^{op})) = (d+r)K. \tag{1.47}$$

Equilibrium under property rights management in the fixed wage payment case is given by

$$(p-c)k(1-F(kN^*)) = (d+r)K + w. \tag{1.48}$$

Assume that $N_{ITQ}^{op} = N^*$. Substituting (1.48) into (1.47) implies that

$$(p-c)(1-x)k(1-F(kN_{ITQ}^{op})) = w. \tag{1.49}$$

However, expected remuneration in operating profit sharing is

$$E[M|x] = (1-x)(p-c)\left[\int_{Q_{min}}^{kN} \frac{Q}{N} f(Q)d(Q) + k(1-F(kN))\right]. \tag{1.50}$$

As long as $\int_{Q_{min}}^{kN} \frac{Q}{N} f(Q)d(Q) > 0$, it must be the case that $E[M|x] > w$ at N^*.

1.9.2 Part B

In this model, consider a vessel's crew to be represented by a single agent. The agent will maximize expected utility which is an increasing function of expected remuneration and is a decreasing function of effort. Assume, then, the following function form of crew utility:

$$
\begin{aligned}
E[U] &= E[M|x,e] - g(e) \\
&= (1-x)(p-c(e))\left[\int_{Q_{min}}^{kN} Qf(Q)d(Q) + k(1-F(kN))\right] - g(e). \qquad (1.51)
\end{aligned}
$$

The crew's problem is therefore to maximize expected utility with respect to their level of effort, e. The crew's first order condition takes the form

$$(1-x)(-c'(e))\left[\int_{Q_{min}}^{kN} \frac{Q}{N}f(Q)d(Q) + k(1-F(kN))\right] - g'(e) = 0 \qquad (1.52)$$

which implies the equilibrium condition

$$(1-x)(-c'(e))\left[\int_{Q_{min}}^{kN} \frac{Q}{N}f(Q)d(Q) + k(1-F(kN))\right] = g'(e). \qquad (1.53)$$

This familiar expression simply says that the marginal benefit of effort is equal to the marginal cost of effort. For added intuition, note that

$$(1-x)\left[\int_{Q_{min}}^{kN} \frac{Q}{N}f(Q)d(Q) + k(1-F(kN))\right] = \frac{g'(e)}{(-c'(e))}. \qquad (1.54)$$

Assuming that $c'(e) < 0$, if the crew share $(1-x)$ increases, then the denominator on the right hand side of equation (11) must decrease. Since $c(e)$ was assumed to be decreasing and strictly convex, that implies that $c'(e)$ will be becoming less negative as effort increases; e.g., $c'(e)$ approaches zero as $e \to \infty$. As a result, $-c'(e)$ will be decreasing in e. This is an intuitive result: as the crew is paid a larger share of the boats profit, they work harder to reduce operating costs. This in turn increases overall profits which may or may not increase the incentive of the quota owner to over-invest; it depends on what share of the increased profits accrue to them versus the crew.[28]

The type of feedback discussed above implies that increasing the scale wage of the crew will detract profits from the boats owner directly, but the feedback effect which occurs through effort will mitigate that effect.

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[28] Note that the tradeoff between income and substitution effects for income famous in New York taxis is not present here. The reason is that within season catch is not modeled as occurring stochastically. A richer model might include such counterintuitive behavior.

Chapter 2

The Structure of Energy Related Research Joint Ventures Between Government and Industry

Abstract

Most developed countries fund national laboratories to perform energy-related R&D. For example, the U.S. Department of Energy's national labs are mandated to perform research in conjunction with U.S. industry aimed at increasing energy efficiency. This paper extends the research joint venture (RJV) literature to cover these government funded energy-related collaborations. It uses a game theoretic framework to explain why a RJV including a national lab will tend to have significantly more participants than a private RJV. The model predicts that regulatory capture is likely to occur from firms that work with national labs in RJVs and receive exogenous funding, such as federal grants, to perform RJV research. Further, it is possible that RJVs including national labs that do not receive exogenous funding are more likely to consist of more heterogeneous firms. The theoretical findings are tested against the Collaborative Research database, a federal registry of all RJVs in the US.

2.1 Introduction

One of the stated goals of the US Department of Energy (DOE) is that it be, "committed to reducing America's dependence on foreign oil and developing energy efficient technologies for buildings, homes, transportation, power systems and industry" (DOE website). In order to achieve this goal, the US DOE funds national laboratories to develop technologies that increase energy efficiency with an budget of roughly $5 billion per anum. Most other OECD countries have similar efforts in place to reduce domestic energy usage in the commercial sector (Almus and Czarnitzki 2003). In addition to the work done at national labs, there are many DOE programs designed to foster innovation carried out by either private firms or private firms working jointly with national labs. The DOE's Industrial Technologies Program (ITP) is one such program, having funded close to $200 million per anum in various research collaborations from 2006-2008 with the aim of developing more energy efficient industrial processes.

In many cases, whether funded by a government program like ITP or not, national labs enter into research joint ventures (RJVs) with private firms. RJVs are federally registered entities comprised of at least two private firms or a private firm and a research institution such as a university or a national lab. The members of RJVs are allowed to share the products of a R&D product with anti-trust impunity due to national law in most OECD countries. While there is a significant literature studying the formation and welfare implications of RJVs between private firms, the role of national labs in RJVs is not well understood.

It is widely accepted that there can be a role for government in R&D insofar as there is a public good aspect to widely implementable basic research and development (R&D). The effects of government R&D projects on basic technologies and the effects of government research contracts, like the Small Business Innovation Research Program (SBIR), on private R&D projects has been studied in some depth (Griliches 1986 and David, Hall and Toole 2000, and Wallsten 2000). While the effects of government funds on the R&D expenditures of private firms have been studied in some depth, the role of government funding in RJVs in unknown. However, it is not clear that the incentives that govern an individual firm's use of government R&D grants are the same as the incentives of an entire RJV, a RJV member firm, or a potential RJV member firm. Further, if the inclusion of a national lab or government funding in a RJV alters composition of its members, then the welfare implications of government R&D projects on RJVs is unclear.

Given that national laboratories account for a significant portion of government expenditures on energy related R&D and national labs frequently work with private industry, understanding the relationship of between labs and firms is important. Firms that work closely with national labs may have access to capital that gives the firm's technology platform a competitive advantage. A group of firms working with national labs, then, could obtain a long run competitive advantage. Alternatively, if national labs are seen as sources of external funding, then the existence of national labs could crowd out private investment in R&D and have little effect except as a direct subsidy to firms.

This research develops a theoretical model explaining how national labs and government funding affects the size and composition of RJVs. The theoretical model developed correctly predicts the relative size of RJVs that include national labs or receive direct government funding or both, when tested against a dataset describing all RJVs registered in the US from 1985-2008. In essence, the inclusion of national labs and exogenous funding affects the relative marginal benefit to RJV member firms of adding additional firms to the RJV. The data imply the following: 1) that national labs are included in RJVs in which firms have heterogeneous technologies and relatively large idiosyncratic costs, 2) that regulatory capture of government funding is prevalent in RJVs that include national labs and are funded by the federal government and 3) that firms are responsive to changing market conditions in RJV formation.

The remainder of this paper is as follows: section two reviews the relevant literature on RJVs, government funded R&D and national labs in order to put the research in context. Section three introduces the theoretical model and presents theoretical results. Section four tests the theoretical model empirically. Section five offers brief concluding remarks including discussing the welfare implications of the theoretical model.

2.2 Literature Review

Due largely to the observed success of Japan's RJVs in the 70s and 80s, US Congress passed the National Cooperative Research Act (NCRA) in 1984, giving firms that form federally registered RJVs impunity from anti-trust laws under the "rule of reason". The passage of the NCRA led to a number of theoretical papers seeking to explain when RJVs are socially desirable versus only privately desirable to firms.

D'Aspremont and Jacquemin (1988) develops a model which finds that RJVs will increase both R&D and quantities in industries where they exist. Conversely, Kamien, Muller and Zang (1992) find that if there are many firms in the RJV, then R&D is likely to fall. The difference in the two findings hinges on the importance of the free-riding problem in firms' R&D effort decisions in addition to the external effect on other firms' costs due to one's own research effort. Both D'Aspremont and Jacquemin (1988) and Kamien, Muller and Zang (1992) examine the implications of RJVs assuming symmetric Cournot competition and assumes that the decision to enter the RJV as already been made by the firm.

Modeling a strategic RJV entry decision by firms allows for analysis of the size of formed RJVs relative to their optimum. Katz (1986) finds that if firms can set R&D cost-sharing rules (e.g., share research facilities) R&D may fall due to the free rider problem. Katz also finds that if spill-overs between firms are likely to be large, then RJVs will increase R&D. Due to these competing effects- in addition to uncertainty over changes in consumer surplus- Katz concludes that general statements about social welfare and RJVs are difficult to make. Sumumura (1992) and Motta (1992) both generalize the D'Aspremont and Jacquemin (1988) model to account for richer market conditions. Atallah (2005) and Poyago-Theotoky (1995) directly address the optimal size of RJVs assuming ex ante identical firms competing Cournot in the output market and finds that large RJVs are generally welfare improving. Leahy and Neary (1997) show the general result that the social benefits of RJVs are likely to be low if firms interact strategically. Interestingly, there is scant evidence that RJV formation has been theoretically examined in the case of asymmetric firms.

Federal labs role in RJVs, and as a research partner more generally, has received little attention in the literature even though the composition of RJVs has been studied in general (Hernan, Marin and Siotis 2003). This is surprising given that the annual budget of US national labs was nearly $5 billion in 2009, roughly in line with historical standards. Leyden and Link (1999) develop a very general theoretical model in which the inclusion of national labs in RJVs shift the cost and benefit curves associated with adding more members to a RJV. Leyden and Link (1999) find that the inclusion of national labs in RJVs suggest that the benefits of the RJV are more difficult for firms to appropriate but that national labs increase the economies of technical scope of R&D. Leyden and Link 1999 attempt to explain the inclusion of national labs in RJVs by using the inclusion of a national lab in a RJV as the dependent variable in a probit model. Leyden and Link (1999) find that large RJVs will include a national lab if 1) national labs decrease the cost of forming RJV and 2) large RJVs reduce the appropriability of RJV R&D output. In order to test the theoretical model, Leyden and Link (1999) use the inclusion of a federal lab as the dependent variable in a probit model econometric model controlling for RJV size, industry and a subset of RJV purpose variables.[1]

Most generally, national labs can be thought of as a source of R&D dedicated capital provided by the government. There is a significant literature on the effects of government funding for R&D on private firm R&D activity. Guellec and De La Potterie (2003) find that the form, level and stability of government funding are all important important. Wallsten (2000) finds evidence that direct grants may crowd out firm R&D dollar for dollar.[2] Lach (2002) finds evidence that government R&D grants crowd out spending of large firms on R&D but stimulates spending of small firms.

This paper will develop a model that explains the role of national laboratories in RJVs including both labs and multiple private firms. Technology space is explicitly modeled such that each firm in an industry has an industry-specific technology and an firm-specific technology leading to asymmetric Cournot market competition. This feature is itself a contribution to the RJV literature. A firm's marginal cost may be lowered due to R&D conducted by RJVs which include federal labs or those that do not. Further, RJV funding is explicitly modeled so that the dynamics of RJVs that either include or exclude national labs and either include or exclude government funding can be examined. The theoretical findings of the model are tested against a data set that contains all federally registered RJVs from 1985-2006.

The next section outlines an analytical model in line with Kamien, Muller and Zang (1992). The fourth section analyzes the model. The fifth section tests the model empirically. Conclusions follow.

2.3 Model

This section introduces the model in sequence, starting with firm technologies, industry industrial structure, government research structure and finishing with the structure of collaboration between government and industry.

Each firm in an industry is assumed to produce a homogenous good using a Leontief production function. Each firm i has an input requirement function $1 = \min[E_i, K, L]$. The first argument E_i represents the amount of energy a firm i requires to produce one unit of output and K and L represent the amount of capital and labor

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[1] Their results can be replicated using the subset of data that was available at that time.

[2] This finding is becoming pervasive in the public economics literature. Turner (2010) find evidence that federal tax-based student aid eliminates aid supplied by a student's university dollar for dollar.

the firm requires to produce one of output. For simplicity, firms use the same production technology for non-energy inputs. Given this specification, each firm has a constant marginal cost $c_i = wL + rK + vE_i$. Note that a firm will only produce if the market price of output, P, is greater than their marginal cost: $P \geq c_i$. Assume that each firm i's unit input requirement for energy, E_i, is the realization of a random variable $E \sim f(E)$. As a result, each firm has idiosyncratic marginal cost, bounded above by price and below by the costs of the other factors of production and minimum energy costs.[3]

Due to the technology assumptions, each firm's marginal cost has two components. The first component is shared by all firms in the industry, $\bar{c}$, and the other is idiosyncratic and firm specific, η_i. Thus, a firm's total marginal cost is defined as $c_i = \bar{c} + \eta_i$ where $\bar{c} = P - wL + rK + v\bar{E}$ and $\eta_i = vE_i$.[4]

Assume there are $i = 1, 2, ..., N$ firms in Cournot market competition. Inverse industry demand is assumed linear:

$$P = \alpha - \beta \sum_{i=1}^{N} q_i. \tag{2.1}$$

Each firm's equilibrium quantity is given by the expression

$$q_i^* = \frac{a + \sum_{j \neq i}^{N} c_j - Nc_i}{(N+1)\beta}. \tag{2.2}$$

Note, then, that the equilibrium profit function for each firm is given by

$$\begin{aligned} \pi_i &= (P(Q^*) - c_i)q_i^* \\ &= \left(\alpha - \beta \left(\sum_{i=1}^{N} \left(\frac{a + \sum_{j \neq i}^{N} c_j - Nc_i}{(N+1)\beta} \right) \right) - c_i \right) \left(\frac{a + \sum_{j \neq i}^{N} c_j - Nc_i}{(N+1)\beta} \right) \\ &= (q_i^*)^2. \end{aligned} \tag{2.3}$$

Because this paper considers the benefits of RJVs, it is important to understand the relative influence in changes in firm shared costs on individual firm profits. Consider the negative of the derivative of equilibrium firm profits of π_i^* with respect to the industry

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[3] While this model assumes a Leontief production function in order to give a bounded, monotonic support for the unit energy input, many other production functions would yield this result. The Leontief function form was assumed for simplicity but the model's results hold so long as the unit requirement energy input is governed by a bounded and strictly monotonic distribution.

[4] The shared energy component, $\bar{E}$, may be thought of as common production processes such as energy use in buildings.

specific cost component, $\bar{c}$ for intuition. The total derivative of firm i's equilibrium profits with respect to a decrease in $\bar{c}$ reduces to:

$$\begin{aligned} -\frac{d\pi_i^*}{d\bar{c}} &= q_i^* - \left(\frac{dP(Q*)}{dQ*} * \Sigma_{j \neq i}\left(\frac{dq_j^*}{d\bar{c}}\right)\right) \\ &= \frac{a + \sum_{j \neq i}^{N} c_j - Nc_i}{(N+1)\beta} - \frac{N-1}{N+1} \end{aligned} \tag{2.4}$$

This expression gives us the intuitive result that a decrease in the component of costs shared by all firms will increase profits for all firms directly from an extra unit of profit for all goods sold and decrease them indirectly due to the shift in a firms residual demand curve from other firms' lower costs. As a result, a decrease in common costs benefits firms with larger market share more significantly than firms with smaller market share. [5] The precise difference in profits enjoyed by firms producing different quantities is

$$\begin{aligned} -\frac{\partial\pi_i^*}{\partial\bar{c}} - \left(-\frac{\partial\pi_j^*}{\partial\bar{c}}\right) &= q_i^* - q_j^* \\ &= \frac{\nu(\eta_j - \eta_i)}{\beta} \end{aligned} \tag{2.5}$$

The increase in firm profit due to a fall in $\bar{c}$ is different across firms insofar as firms supply different equilibrium quantities due to their unique idiosyncratic costs and demand is responsive to changes in prices, represented by β.

2.3.1 The Role of National Labs

The decision of whether to include a national lab in a RJV is jointly made by RJV member firms and the lab. This section focuses on the decision to include a national lab in a RJV. The general role of national labs is not explicitly modeled, only their role insofar as they are relevant for RJVs.[6]

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[5] If total derivative is actually derived, we find that it equals to $(P(Q^*) - c_i)\left(\frac{1}{((N+1)\beta)}\right) - q_i^* \frac{N}{N+1} + q_i^*$. The first term shows the indirect increase in firm i profits due to an increase in q_i^*. The second term in equation 4 shows the indirect decrease in firm i profits due to a fall in $P(Q^*)$ from the direct effect on quantity and indirect effect from change in quantity due to the fall $\bar{c}$. Equation 4 can be thought of a version of the envelope theorem where there are two direct effects, one due to the quantity supplied of firm i and another from the strategic effect of the other firms in the market.

[6] In the US, national labs are funded directly by the US government and also perform contract work for a variety of clients.

In this model, national labs act as active participants in RJVs in addition to obtaining information about production processes in order to allow for a larger degree of appropriability of energy reducing technologies. As an active participant, national labs contribute costly resources such as physical and human capital to the RJV directly, which weakly increases the effectiveness of any RJV. In obtaining information about RJV member firms' production processes, national labs seek to select and organize research projects that can be appropriated by all member firms as effectively as possible.

Assume that there is a set of production technologies that take some set of inputs and turn them into a single output. Each firm has asymmetric information about the set of production technologies that exist and selects the production technology from the set they observe the minimizes unit costs. Formally assume there exists a family of homogeneous of degree one functions $\tilde{F}$ s.t. $\forall \tilde{f} \in \tilde{F} : R^M \to R$ where m is the size of the vector of inputs, $\underline{x}$. Assume there is an associated vector of input prices $\underline{w}$ faced by all firms.

Each firm i is defined by a particular subset $\tilde{F}_i \subset \tilde{F}$. Selection of a particular unit production function $\tilde{f}_i^* \in \tilde{F}_i$ is determined by which production function minimizes the cost of producing one unit of output. Formally, the choice of $\tilde{f}_i^*$ minimizes $\underline{w} \cdot \underline{x}$ such that $\tilde{f}_i(\underline{x}) = 1$. Homogeneity of degree one implies that each firm will have a constant marginal cost $c_i = \underline{w} \cdot \underline{x_i}$ such that $\tilde{f}_i^*(\underline{x}) = 1$. Therefore, each firm is defined by an idiosyncratic subset of the technologies. By earlier assumption, the capital and labor inputs (or more generally $m - 1$ inputs) are the same for all technologies so that it is only the energy input that is idiosyncratic across firms.[7]

Figure 1 gives an example of the technology space described here given a Leontief input requirement function and two inputs, capital and energy. In figure 1, only technology over the energy input is subject to any form of firm specific idiosyncracy. Figure one shows that firm j's technology endowment is a proper subset of firm i's technology endowment. As a result, the level of energy required to make one unit of output by firm j is $\eta_j - \eta_i$ greater than the energy input requirement of firm i.

In this model, the government lab aggregates information to discover what are the common components to each firm's production process without releasing information about each firm's production technology to other firms.[8] The government may spend

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[7] Allowing for a richer set of heterogenous technologies leads to a frontier of possible technologies that or in production. This possibility is left to future research.

[8] While an optimal public policy might involve direct subsidies to firms as well, this research is concerned with the role of national labs in RJVs. Refer to the literature review for a list of publications

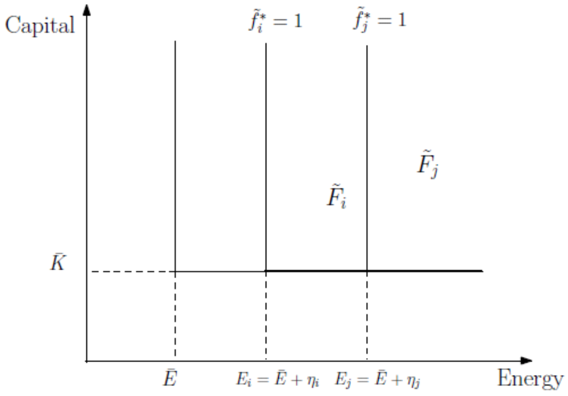

Figure 2.1: Technology Space

Figure 2.1: Technology Space

resources on research through national labs to reduce the shared cost component of firms, $\bar{c}$ and specifically the common cost component derived from energy. The effectiveness of such research is governed by the ability of firms to appropriate research output created in tandem with the national lab and the sum of resources used. Trivially, for research to be effectively integrated into a firm's production process, it must improve a technology already used by a firm. For example, in order for a energy cost reducing technology to be deployed to all photovoltaic (PV) companies, the technology must deal with component of the production process that is used by all PV companies in their production or final product.

Upon joining a RJV with a national lab, a firm i reveals its unit production function, $f_i(\cdot)$ to the national lab. This can be thought of as letting federal scientists view the entire production process of the firm. A priori, both firms and the national lab are uncertain about which aspects of the production process are shared by other firms and which are idiosyncratic to firm i. The objective of national labs in this model is to accumulate as much information as possible about shared industry inputs and technologies to perform research that can be effectively used at reducing those inputs and improving those technologies common to all RJV members. In this model, national labs help to direct and organize research projects by comparing the technology used by

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examining the impact of direct subsidies on firm R&D activities.

each individual firm the RJV in order to deduce which how research can be most useful.

Recalling that $c_i = \bar{c} + \eta_i$, the government knows with certainty the upper bound of any individual firm's total cost, $c^{MAX} = P$. Assume that the government knows the structure of the distribution of idiosyncratic costs and for the purposes of exposition, assume idiosyncratic costs are uniformly distributed such that $\eta_i \sim U[0, \eta_{max}]$. Given this functional form assumption, each firm's marginal cost $c_i \sim U[wL + rK + v\bar{E}, P]$. If n firms in an industry join a RJV with the national lab, the national lab observes a set of production functions which monotonically map inputs to costs. As such, the national lab observes a set of realized random variables $\{c_i\}_{i=1}^{n}$ associated by the most efficient technologies, $\tilde{f}_i^*$.

The national lab must infer what technologies are shared by all firms. The unit input requirement function for a firm i is $1 = \min[E_i, K, L]$ where $E_i \sim U[\bar{E}, \frac{P - wL + rK}{v}]$. If national lab research improves the technology common to the entire industry then the benefits of R&D can be appropriated by all RJV members and the common energy component of industry inputs, $\bar{E}$ falls. Thus, the national lab increases appropriability of research by accurately estimating the common elements of production $\bar{E}$ and common technologies used in production. Since the labor and capital inputs are assumed identical across all firms in an industry, the national lab can estimate $\bar{c}$ since it maps monotonically to technology space. In effect, then, the national lab increases appropriability of research by better estimating the lower bound of a uniformly distributed random variable $c_i \sim U[\bar{c}, P]$. Equivalently, the national lab estimates the upper bound of a random variable $\eta \sim U[0, P - \bar{c}]$. As the appropriability of research projects increases, so does the magnitude of the decrease in costs associated with the research project.

Consider a discrete time model where costs in period one are related to initial period zero costs, the appropriability of the research project chosen, $\bar{c}_0$, relative to actual shared technology, $\bar{c}$, and resources dedicated to the RJV, R:

$$\bar{c}_1 = \bar{c}_1 \left(R; d\left(\bar{c}_0 - \bar{c}\right)\right). \tag{2.6}$$

where $d(\cdot)$ is some loss function. Assume that $\frac{\partial \bar{c}_1}{\partial R} \leq 0$, $\frac{\partial \bar{c}_1}{\partial d} \leq 0$, and $\frac{\partial^2 \bar{c}_1}{\partial R \partial d} > 0$. In words, the first assumption means that more research dollars weakly decrease next period's cost associated with the common technology. The second assumption implies that as the distance between a The last assumption means that as the government's choice of $\bar{c}_0$ gets closer to the true $\bar{c}$, a set amount of research dollars will always reduce

$\bar{c}_1$ by more.

2.4 Theoretical Results

For the purposes of exposition, assume the loss function takes the form

$$d(\bar{c}_0 - \bar{c}) = (\bar{c}_0 - \bar{c})^2. \tag{2.7}$$

Equation (2.7) is the familiar expression for the mean square error if $\bar{c}_0$ is an estimator of $\bar{c}$. Given that the idiosyncratic component of costs η are distributed $\eta \sim U[0, P - \bar{c}]$. The appendix shows the expected mean square error as a function of the number of observations n is

$$E(\bar{c}_0 - \bar{c})^2 = \frac{2(P - \bar{c})^2}{(n+2)(1+n)}. \tag{2.8}$$

Finally, assume that the function $\bar{c}_1(\cdot)$ takes the form

$$\bar{c}_1 = min\left[\bar{c}, \frac{k}{R}(\bar{c} - \bar{c}_0)^2\right]. \tag{2.9}$$

In this specification k is a scaling factor and the number of observations n is the size of the RJV. The assumption of firms being able to research independently will only change the opportunity cost of RJV entry and not affect any of the dynamics presented in this model. The implication of these functional form assumptions is that the benefit of a RJV is concave in the number of member firms, n

Given this national lab RJV structure, a firm's quantity supplied to the market upon entering a non-trivial RJV of size n will always increase:

Lemma 1:

For a given RJV size $n < N$, a firm will always produce weakly more output if they enter a non-trivial RJV than if they do not.

The proof is in the appendix. This result is not at all surprising as Cournot equilibrium quantities are decreasing in firms own costs. Because appropriability is explicitly taken into account in this model, though, the dynamics across RJVs of different sizes present themselves in a unique way. It is possible that the fall in price due to increased quantity supplied can drive firms with high idiosyncratic costs out of the market.

Firms decide whether to enter or to not enter RJVs with national labs by comparing their expected profits from entering versus not entering. Assume that there is a cost that all firms incur for entering the national lab RJV, Φ. Φ can be thought of as a time cost of firm researchers. [9] Consider a firm i making the decision between entering versus not entering a national lab RJV consisting of n firms in a market of size $N > n$. Given there assumptions, a firm i considers the following profits of entry (π_i^{RJV}) verses non-entry ($\pi_i^{\neg RJV}$)into a national lab RJV:

$$\begin{aligned} \pi_i^{*,RJV} &= (q_i^{RJV})^2 - \Phi \\ &= \left(\frac{\alpha + v\frac{2kn(P-\bar{c})^2}{R(n+1)(n+2)} + v\Sigma_{j=1}^{j}\eta_j + \Sigma_{j=n+1}^{N-1}c_j - Nv\frac{2kn(P-\bar{c})^2}{R(n+1)(n+2)} - N\eta_i}{(N+1)\beta} \right)^2 - \Phi \\ \pi_i^{*,\neg RJV} &= (q_i^{\neg RJV})^2 = \left(\frac{\alpha + v\frac{2kn(P-\bar{c})^2}{R(n+1)(n+2)} + v\Sigma_{j=1}^{j}\eta_j + \Sigma_{j=n+1}^{N-1}c_j - Nc_i}{(N+1)\beta} \right)^2 \end{aligned}$$

These assumptions imply the following result:

Proposition 1:

For any cost distribution, there is a range of RJV entry costs that cause no firms enter the RJV, that cause some firms to enter, and cause all firms to enter. If only some firms enter, those firms will be lower cost firms.

The proof is in the appendix. Intuitively, firms with lower idiosyncratic costs benefit disproportionately for lowered common costs of production because they produce a higher quantity. Higher cost firms do not have an incentive to spend resources entering the RJV. The range of fees that bisect industry firms into those who enter and those that don't is decreasing in both industry size and the steepness of the demand curve and increasing in the range of idiosyncratic costs. As a result, in industries facing an inelastic demand curve, there could be long run competitive effects caused by the existence of RJVs including national labs.

Proposition 1 implies that a policy maker should account for the competitive effects caused by RJVs that reduce industry common costs. If newer technologies have the potential to create long run energy savings but have large idiosyncratic costs initially, then these firms would be harmed by reduced costs of firms with lower idiosyncratic costs. As such it might be optimal forthe policy maker to facilitate a portfolio of RJV

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[9] It is common for researchers at firms working with national labs to spend significant time in collaboration projects with them. It is also possible that firms develop cost sharing rules in RJVs with national labs a la Katz (1986). in funded RJVs, there is generally a cost sharing rule that must be in place in order to be eligible for funding.

projects.[10] In the case of the US Department of Energy one aimed at reducing large firms energy usage and another aimed at reducing new technology firms idiosyncratic costs.

It is not surprising that equilibrium RJVs size in Proposition 1 is a function of industry characteristics. An increase in input prices can increase the benefit of RJV entry and thereby increase the size of RJVs. Demand curve elasticities are shown to be an important parameter in equilibrium RJV size; in markets facing more inelastic demand curves, the chance that firms don't have an incentive to enter RJVs grows.

While Proposition 1 deals with the composition of RJVs that include national labs, it does not directly address the size of RJVs that include national labs versus those that do not, nor the effect of exogenous funding on the size of RJVs including national labs. Assume that the total funding of a RJV is the sum of each member firm's individual cost of joining, Φ. The R&D technology is assumed to be the same in either RJV but a RJV of size n that does not include a national lab has the right to refuse admittance to a marginal member. Consider the profits of a member i of a RJV of size n which doesn't include a national lab:

$$\begin{aligned} \pi_i &= (q_i^*)^2 - \Phi \qquad (2.10) \\ q_i^* &= \frac{\alpha + v\frac{2kn(P-\bar{c})^2}{n\Phi(n+1)(n+2)} + v\Sigma_{j=1}^{j}\eta_j + (N-(n+1))\bar{c} + \Sigma_{j=n+1}^{N-1}\eta_j}{(N+1)\beta} \\ &\quad \frac{-N(v\frac{2kn(P-\bar{c})^2}{n\Phi(n+1)(n+2)} - \eta_i)}{(N+1)\beta} \end{aligned}$$

Firm i will always accept another firm into the RJV so long as the derivative of firm profits with respect to n is greater than zero. This intuition leads directly to Proposition 2.

Proposition 2:

For any market size N in which a private RJV is productive and is rationalizable by at least two firms $n < N$, there is a convex set in parameter space (marginal productivity of R&D, range of idiosyncratic costs and RJV entry costs) such that the members already in the RJV will exclude additional members. The size of the RJV needed to block further entry is increasing in the productivity of R&D and the size of idiosyncratic costs relative to shared industry costs and decreasing in RJV entry costs.

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[10] In a more general technology space, this would amount to facilitating RJVs by firms with "close" technologies.

The proof is in the appendix. Intuitively, the benefit that accrues to a firm in the RJV when another firm enters is derived from both the additional firm's contribution to funding, Φ, and the additional precision with which the entire RJV can select research projects. The cost associated with another firm entering is the decrease in price associated with the increases in quantity supplied to the market by the marginal firm. When these two effects cancel the firms already in the RJV will be opposed to allowing another entrant.

Perhaps most striking about this finding is that while the level of marginal profits with respect to RJV size of a member firm is affected by the steepness of the market demand curve, the sign is not. Put another way, there is no interaction between the steepness of a member firm's residual demand curve and the size of the RJV. Intuitively, in industries characterized by a large range of idiosyncratic costs, $(P - \bar{c})$ and R&D projects with large potential benefits, the increase in profit due to lower own costs is greater than the decrease in profit due to a competitor's increase in quantity supplied from their cost reduction. Finally, an increase in the cost to joining a RJV, Φ, will reduce the size of a RJV needed to prevent further entry because all other firms benefit from the increase in research resources contributed by the new firm in addition to the entering firm benefiting from the research resources of all previously entered RJV members.

It is important to note that Proposition 1 addresses the incentive of a firm to enter any RJV while Proposition 2 addresses the incentive of firms in a RJV to invite additional members. It is possible that the marginal firm that does not have an incentive to enter a RJV from Proposition 1 would be invited to enter a RJV. Alternatively, it is possible that a low cost firm would have an incentive to enter a RJV but would not be invited to do so. The propositions make no claim as to when the former rather than the latter situation would occur.

Proposition 2 states that for any exclusive RJV, there is a subset of firms that will will block further entry, the relative size of blocking coalitions in different situations is addressed in the following corollaries.

Corollary 1:

An exclusive RJV that includes a national lab with exogenous funding will always have fewer members than a RJV which includes a national lab but doesn't have exogenous funding.

Corollary 2:

Consider RJVs with no exogenous funding: exclusive RJVs including national labs will be larger than RJVs without national labs if RJVs including labs have on average 1) lower entry fees Φ, 2) higher productivity k or 3) are selected by firms farther away from each other in technology space ($P - \bar{c}$ large).

The proofs are in the appendix. With respect to Corollary 1, an exclusive RJV that includes a national lab and has exogenous funding will always be smaller than a RJV that doesn't have exogenous funding because the resources gained by adding a marginal firm are offset by the resources which are garnered by including a national lab and funding. As such, if national labs are better able to attract federal research grants, we would expect them to be included in small RJVs and RJVs between only one firm and a national lab. This result is consistent with the literature on regulatory capture of public R&D funds. Further, it is consistent with the Leyden and Link (1999) notion that national labs are better at acquiring federal funds.

While Corollary 1 is concerned with the the relative size of national lab RJVs that include versus exclude exogenous funding, Corollary 2 addresses the relative size of RJVs that include versus exclude national labs. Corollary 2 defines the characteristics of RJVs projects that include versus exclude national labs insofar as they affect equilibrium RJVs size. Most intriguing is that if RJVs including national labs are researching projects that seek to address common technologies of members firms in an industry where individual firms have distinct technologies, or in industries where $(P - \bar{c})$ is large, then RJVs that include national labs would be expected to be large.

In sum, the theoretical model presented here implies that industry characteristics, the form of national lab inclusion in a RJV and the funding requirements of RJV formation are all important in determining the size and the private and social benefits of a RJV. Further, the model predicts that exogenous funding will decrease the size of RJVs and makes explicit the implications of finding differently sized RJVs for RJVs that include versus exclude national labs but are not funded. These implications will be tested empirically in the next section.

2.5 Empirical Analysis

The implications of the theoretical model in the preceding section are now tested against a data set that contains all RJVs registered with the US government from 1985-2006, the years for which data are available.

The passage of the National Cooperative Research Act (NCRA) of 1984 relaxed anti-trust laws in the US as they pertained to cooperation between firms in R&D activities in the US. In order to qualify for anti-trust law indemnity under the act, all RJVs must file with a Federal Registry. Data from the filings was collected from 1985-2006 in the COllaborative REsearch database (CORE) via National Science Foundation (NSF) funding. For each RJV, the database includes the number of RJV members, RJV industry, RJV goal, year of registration, and some information on the composition of RJV members such as if a National Laboratory or University.

The CORE database also includes a binary variable indicating whether the RJV was funded by the Advanced Technology Program (ATP) via the National Institute of Standards and Technology (NIST).[11] This federal program administered through the US Commerce Department is an important source of R&D funding accounting for an average of over $160 million annually since 1990. In order to qualify for ATP funding, a RJV must consist of at least two private firms, the private firms must contribute toward a matching-fund requirement, and have a well-defined research agenda. Firms do not need be in a federally registered RJV to jointly submit proposals for ATP funding, but many are. When submitting ATP proposals, firms may choose to include either national labs or universities or both. The CORE database consists of a subsample of ATP funded RJVs that were federally registered and ATP funded at the time of filing.

Table 2.1: US RJV Summary Statistics, 1985-2006

	RJV Includes National Lab	RJV Excludes National Lab	All RJVs
Observations	122	840	952
Ave. Number Members	22.02	11.96	13.24
NIST Funded	76	3	79
Process Driven	58	432	490
Product Driven	40	338	388

Data from CORE database, 1985-2006.

Table 1 shows summary statistics from the CORE database by RJVs that include a national lab, those that don't and the sum over all RJVs for all years in which data is available. Immediate is that RJVs that include national labs have almost twice as many members as those that don't. Further, over 95% of RJVs that have NIST funding through

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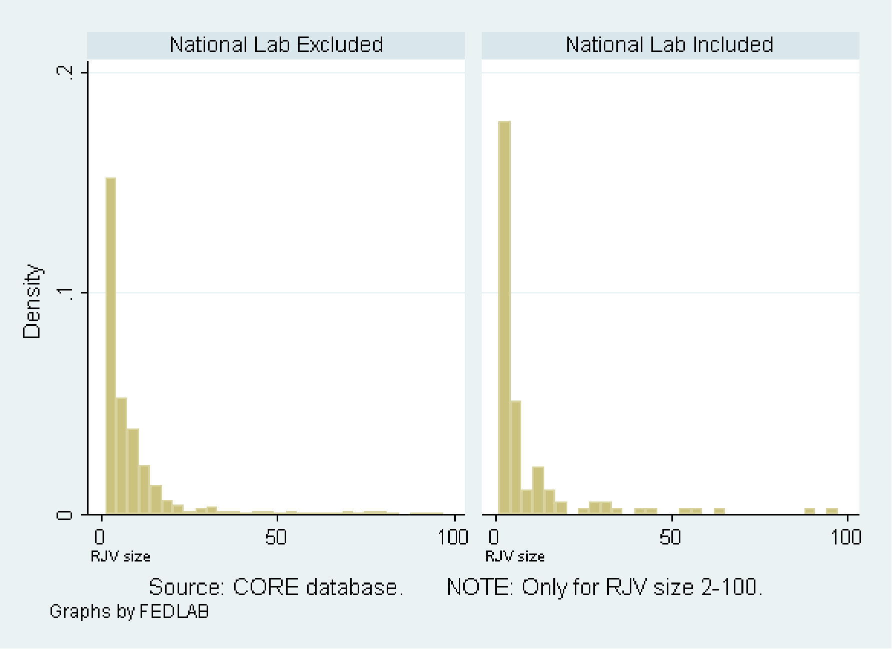
[11] Since 2007, the ATP has been replaced by the Technology Innovation Program (TIP) which performs similar functions.

the ATP include a national lab. There is no clear relationship between the inclusion of a national lab in a RJV and whether a RJV is created to improve an industry's product or an industry's process. This motivates the general model of the role of National Labs in RJVs.

For exposition, figure 2 is a histogram of RJV size conditional on the exclusion and inclusion of a national lab for RJVs that have 100 members or less.[12] Comparing the two histograms, there is significantly more weight in larger RJVs for RJVs that include national labs. In RJVs excluding a national lab, there is also a clear decreasing relationship between the size of RJVs and their frequency.



Source: CORE database. NOTE: Only for RJV size 2-100.

Graphs by FEDLAB

Figure 2.2: Histogram of RJV size by inclusion of National Lab

The preceding section developed a theoretical model which makes predictions about the size and composition of RJVs that include and don't include national labs. The findings of the theoretical model include that, conditional on industry characteristics, if firms cannot be excluded at the time of forming a RJV that includes a national lab and if there is a fixed cost to joining, some high cost firms might not join. Conversely, if firms can form an exclusive RJV that doesn't include a RJV, there is an equilibrium size

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[12] Only 21 of 952 observations had RJVs greater than 100 and in order to highlight the differences for RJVs that were not outliers, a size of 100 was used as an upper bound.

for that RJV such that member firms block further entry. Finally, if firms can form an exclusive RJV that includes a national lab, the RJV will be even smaller. That reason for the last result is due to the funding added by the national lab making the resources contributed by a marginal firm less valuable.

To test the theoretical predictions of the model, the econometric specification in this paper exploits a variable indicating whether ATP or NIST funding was at some time involved in the RJV. As stated above, ATP funding inclusion in the RJV dictates cost sharing rules by RJV members. Due to the timing of RJV federal registry filing, if RJVs are recorded as including NIST and national lab involvement it implies that the NIST and the national lab were involved at time of RJV formation. As such, the RJV formation process recorded in the data closely mirrors the theoretical model in the preceding section.

Consider the following cross-sectional econometric specification to test the implications of the preceding theoretical model where i indexes a federally registered RJV:

$$\begin{aligned} size_{it} = \alpha &+ \Sigma_{j=1}^{J} industry_j \delta_j + lab_i \beta_1 + NIST_i \beta_2 + lab_i * NIST_i \beta_3 + energy_i \beta_4 \\ &+ \Sigma_{n=1}^{N} energy_i * energyprices_{t-n} \phi_n + \underline{x_i}' \underline{\psi} + \epsilon_{it}. \end{aligned} \tag{2.11}$$

In equation (2.11) the *industry* variable is a binary variable indicating the two-digit sic code of the RJV, of which there are 19 recorded. The variables lab_i and $NIST_i$ are binary variables which equal one if RJV i includes a national lab or if RJV i was funded by a NIST program, respectively. Also, included in the regression specification is an interaction of these binary variables. In order to address energy research explicitly, regression specifications include a binary variable indicating if the primary purpose of the RJV is to reduce energy costs of member firms. Finally, a lagged energy price inflation index for intermediate good producers is interacted with the energy binary variable. A positive coefficient on this variable would indicate that the size RJVs formed to reduce energy costs increases as energy costs increase.[13] The main coefficients of interest are the coefficients on lab_i, $NIST_i$, their interaction and the coefficient on the interaction of lagged energy prices .

The dependent variable in specifications (1)-(4) is the number of firms registered in the RJV. In specifications (5) and (6) the dependent variable is the log of the RJV

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[13] These data were taken from the US Energy Information Administration website and matched to the CORE database by the appropriate year: http://www.eia.doe.gov/emeu/aer/finan.html.

Table 2.2: Regression Results

	(1)	(2)	(3)	(4)	(5)	(6)
Lab	33.54***	33.75***	37.83***	38.26***	.993***	.962***
	(13.35)	(12.98)	(13.97)	(13.61)	(.216)	(.219)
NIST	-37.5***	-35.81***	23.17	27.92	.878	.744
	(13.24)	(12.39)	(22.94)	(21.19)	(.984)	(1.01)
NIST*Lab			-67.04**	-70.24***	-2.21**	-2.11**
			(27.06)	(25.65)	(1.01)	(1.04)
Energy	-3.34	-3.19	-3.92	-3.25	-.134	-.279
	(5.44)	(5.67)	(5.46)	(5.64)	(.139)	(1.81)
Energy*$Price_{t-1}$						-3.33
						(4.51)
Energy*$Price_{t-2}$						9.38*
						(4.98)
industry FE	Y	Y	Y	Y	Y	Y
Pr(> partial F)	0.00	0.011	0.00	.012	0.00	0.00
year FE	N	Y	N	Y	Y	N
Observations	961	961	961	961	961	961
r^2	.11	.143	.12	.155	.202	.177

Data from CORE database, 1985-2006.

***= significant at 1%, ** = significant at 5%, * = significant at 10%.

Robust standard errors in parentheses.

size.[14] Regressions (1) and (2) are specifications showing estimates caused by excluding the NIST and National Lab interaction term excluding and including year fixed effects respectively. The difference in means of RJVs which include a national lab and those that are funded by the NIST is statistically significant. The difference between RJVs with a stated primary focus of reducing energy usage and RJVs not stating energy reduction as a primary objective is not statistically significant in these two specifications or any others. This implies that R&D aimed at energy reduction does not significantly alter the size of RJVs relative to any other type of common cost reducing or product improving RJV.

Specifications (3) and (4) include an interaction term between the national lab binary variable and the NIST binary variable. In both specifications, the coefficent on this variable is significant and its inclusion causes the coefficient on the NIST binary to become insignificant. This is not unsuprising as there are only three registered RJVs which are funded through the NIST but do not include a national lab as a member. While RJVs that include national labs are larger than those that do not, if RJVs that include national labs are also funded then they are significantly smaller, controlling for industry type. Such is the prediction of Corollary 1 in the preceding section. Specification (5) affirms this prediction using the natural log of RJV size as the dependent variable. In specifications (3)-(5) the coefficient on the energy binary variable is not significant.

Specification (6) includes an interaction of the energy binary variable and lagged energy prices and has the log of RJV size as the dependent variable. While the estimated coefficients on the energy binary and one year lagged energy price inflation are not significant, the coefficient on two year lagged energy price inflation and the energy binary is significant and large in magnitude. The proper interpretation of this coefficient is that for a 10% increase in energy prices, RJVs with an energy objective are expected to increase in size by 90%.[15] The implication of this finding is that marginal firms are induced to join RJVs as the benefits of doing so increase. This is evidence of Proposition 1: there is a marginal firm for which they are indifferent between entering and not entering and can be induced to enter if input prices change. Further, a partial F-test

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[14] When RJVs of size larger than 100 are excluded, all coefficients of interest maintain their significance and sign. Left-censored Tobit specifications were also executed and yielded no significantly different results.

[15] The highest highest yearly increase was 9%. Two stage least squares was also used with prices instrumenting for the energy binary variable and the variable did become positive and significant in that specification as well. The coefficient estimate using only a one year lag interacted with the energy binary variable had a significant sign of the same sign.

on the set industry indicator variables was statistically significant in every specification. The implication is that if the relative benefit of cost savings or product improvement vary by industry, then RJV size varies as well due to the marginal member opting out.

2.6 Conclusion

This paper seeks to develop a theory describing the role of national laboratories and government funding in the formation of RJVs. This research adds to both the RJV literature by extending previous models of research collaboration in modeling explicitly modeling both technology space and the implications of asymmetric costs in RJV formation. It extends the literature on energy policy by examining the role of national labs, and government resources more generally, as part of a OECD nation's comprehensive energy strategy. Theoretical predictions of the model, that regulatory capture of government funds may occur when RJV R&D is directly funded insofar as firms are excluded from the RJV, are supported by the data. The model and data also imply that industrial structure and input costs are a significant factor in RJV formation and that national labs are included in a unique type of projects, rather than affect the appropriability of RJV research directly.

While the predictions of the theoretical model are supported, more research is needed in order to determine the precise nature of how national labs add value to RJVs. Specifically, there is no way to distinguish between the competing hypotheses that national labs are better able to organize and facilitate research between large groups or if national labs have other research resources that induce more firms to enter RJVs with them. Further, the model in this paper is not inconsistent with the hypothesis of Leyden and Link (1999) that RJV R&D performed with national labs is less appropriable to member firms. Instead, this paper proposes a model where the national lab research is able to make a specific type of research more appropriable as the number of member firms increase, hence inducing firms to include a national lab in those types of projects.

Further, this paper extends the literature on the equilibrium size of RJVs, notably Poyago-Theotiky (1995). If RJVs are modeled as excludable clubs, then direct R&D subsidies are theorized to always cause a decrease in RJV size. This theoretical finding is supported in the data as RJVs that are funded and include a national lab are significantly smaller than those that do not. Further, the data support modeling the decision to form RJVs as a dynamic process since industry characteristics are an important factor in determining RJV size. Further, firms are shown to respond to changing relative prices in how they form RJVs, supporting the prediction of the theoretical model that firms can be ordered by highest to lowest benefit of RJV entrance.

There are some notable drawbacks to the approach used in this paper. Most prominent is the use of the number of firms in the RJV as the measure of RJV size. Using revenues or market share of member firms would allow for more rigorous analysis of the formation of RJVs but such information is not available in any data set known to this researcher. Also, the theoretical model is highly parametric, even though the functional forms used give the model flexibility. Finally, future research should include the policy maker's problem; of specific interest is the optimal number of RJVs in an industry.

While this research does provide evidence of significant competitive effects in RJV formation and regulatory capture, it leaves open questions about how national labs and direct R&D subsidies fit in to the portfolio of a comprehensive energy policy for an OECD country. Specifically, the role of national labs in a social welfare maximization problem is absent. For example, the model developed here cannot predict whether new or old technology platforms in an industry are more likely to receive R&D subsidies. If the benefit of R&D dedicated toward new technologies are potentially large but not immediate, then R&D dedicated to marginal improvements of older technologies would be preferred if the government has a large discount rate. In that case, regulatory capture of national lab R&D resources by mature firms would be not entirely undesirable from the national lab's perspective.

2.7 Appendix

2.7.1 A: Finite Sample Properties of $\hat{\theta}$

Consider a sequence of random variables x_i distributed uniformly such that

$$x_i \sim \quad U[\theta, K] \quad \forall i = 1, ..., N. \tag{2.12}$$

Consider, now, a maximum likelihood estimator $\hat{\theta}$ of the true parameter θ given that K is known with certainty. Rather than estimating the minimum of this range, it is more convenient to define a new random variable, $y_i = K - x_i$. The distribution of of the newly defined random variable is

$$y_i \sim \quad U[0, K - \theta] \quad \forall i = 1, ..., N. \tag{2.13}$$

Call $F(Y|\theta, K)$ the cdf of the random variable y. Define z as the maximum of y subject to a cdf $G(Z|\theta, K)$. For the new random variable, we estimate the upper bound $K - \theta$. The expected value of such an estimator$K - \hat{\theta}$ may be derived as follows:

$$\begin{aligned}
E(Y_{(n)}) &= Pr(\forall \;\; y_i \; i = 1, ..., n \leq z) \\
&= G(Z|\theta, K) = \left(\frac{z}{K - \theta}\right)^n \\
\rightarrow E(Z) &= \int_0^{K-\theta} t \frac{\partial \tilde{G}^n(t)}{\partial t} dt \\
&= \frac{n}{(K - \theta)^n} \int_0^{K-\theta} t^n dt \\
&= \frac{n}{1 + n}(K - \theta) \qquad (2.14)
\end{aligned}$$

Changing variables to find the estimate of the lower bound of the random variable X, we note that $E[Z] = K - E[\hat{\theta}]$ which implies

$$\hat{\theta} = K - \frac{n}{1 + n}(K - \theta) = \frac{K + n\theta}{1 + n} \tag{2.15}$$

Note that this estimator is consistent.The final expression shows the common result that the lower bound estimator is, ex ante, a weighted average of the known parameter and the unknown parameter. It is clear by inspection that the bias of this estimator is

$$E(\hat{\theta}) - \theta = \frac{K + n\theta}{n+1} - \frac{\theta(1+n)}{1+n} = \frac{K-\theta}{1+n} \tag{2.16}$$

This expression shows the intuitive result that the MLE estimator will be upward biased and that the bias converges to zero as the sample size approaches infinity.

To find the second moment of the estimator, we again find the second moment of the upper bound estimator of the random variable Y.

$$\begin{aligned}
E(Z^2) &= \int_0^{K-\theta} t^2 \frac{\partial \tilde{G}^n(t)}{\partial t} dt \\
&= \frac{n(K-\theta)^2}{n+2} \\
\rightarrow var(E(K-\hat{\theta})) &= \frac{n(K-\theta)^2}{n+2} - \frac{n^2}{(1+n)^2}(K-\theta)^2 \\
var(\hat{\theta}) &= (K-\theta)^2 \frac{n}{(n+2)(n+1)^2} \qquad (2.17)
\end{aligned}$$

We can now derive the expected loss associated with a RJV project selection procedure as a function of parameters and the number of entrants into the collaboration.

$$\begin{aligned}
MSE(\hat{\theta}|\theta, K) &= (\hat{\theta}-\theta)^2 + var(\hat{\theta}) \\
&= \frac{(K-\theta)^2}{(1+n)^2} + (K-\theta)^2 \frac{n}{(n+2)(1+n)^2} \\
&= \frac{(n+2)(K-\theta)^2 + n(K-\theta)^2}{(n+2)(1+n)^2} \\
&= \frac{2(n+1)(K-\theta)^2}{(n+2)(1+n)^2} \\
&= \frac{2(K-\theta)^2}{(n+2)(1+n)}
\end{aligned} \tag{2.18}$$

Lemma 1:

For a given RJV size $n < N$, a firm will always produce weakly more output if they enter a non-trivial RJV than if they do not.

Proof: Consider a RJV of size $n < N$. Assume that given n and R, $\bar{c} > \frac{k}{R}(\bar{c} - \bar{c}_0)^2$ so that the RJV is productive. Order the firms such that the first n firms are in the RJV and the set of firms $n+1$ to $N-1$ are not. The final firm is firm i. The cournot equilibrium quantity if firm i enters the RJV is:

$$q_i^{RJV} = \frac{v\frac{2kn(P-\bar{c})^2}{R(n+1)(n+2)} + v\Sigma_{j=1}^{j}\eta_j + \Sigma_{j=n+1}^{N-1}c_j - Nv\frac{2kn(P-\bar{c})^2}{R(n+1)(n+2)} - N\eta_i}{(N+1)\beta}. \tag{2.19}$$

The cournot equilibrium quantity if firm i does not enter the RJV is:

$$q_i^{\neg RJV} = \frac{v\frac{2kn(P-\bar{c})^2}{R(n+1)(n+2)} + v\Sigma_{j=1}^{j}\eta_j + \Sigma_{j=n+1}^{N-1}c_j - Nc_i}{(N+1)\beta}. \tag{2.20}$$

By definition, the difference in quantities is:

$$q_i^{RJV} - q_i^{\neg RJV} = \frac{Nv(\bar{c} - \frac{k2(P-\bar{c})^2}{R(n+1)(n+2)})}{(N+1)\beta} \equiv \Delta_{RJV} \tag{2.21}$$

By the assumption that research has some positive benefit, the numerator is greater than zero giving the desired result.

Proposition 1:

For any cost distribution, there is a range of RJV entry costs that cause no firms to enter, that cause some firms to enter, and cause all firms to enter. If only some firms enter, those firms will be lower cost firms.

If there is an entry cost Φ associated with entry into a RJV with a national lab, equilibrium profits for a firm i in the two stage entry game can be expressed as $\pi_i = \delta^{-1}(q_i^*)^2 - \phi$. Lemma 1 implies that

$$\delta^{-1}(q_i^{*RJV})^2 > \delta^{-1}(q_i^{*\neg RJV})^2. \tag{2.22}$$

Order all firms $i = 1, 2, ..., N$ by the magnitude of their idiosyncratic costs such that $\eta_1 < \eta_2 < ... < \eta_N$. For a given firm j, define ϕ_j such that

$$\phi_j \equiv \delta^{-1}(q_j^{*RJV})^2 - \delta^{-1}(q_j^{*\neg RJV})^2. \tag{2.23}$$

Intuitively, if there is a cost to firm j of entering the RJV less than ϕ_j, firm j enters and if the cost of entering the RJV is greater than ϕ_j the firm will not.

Lemma 1 shows that for a given number of firms in the RJV n that $\Delta_{RJV} = q_k^{*RJV} - q_k^{*\neg RJV} \forall k = 1, 2...N$. Algebraic manipulation shows that

$$(q_k^{*RJV})^2 - (q_k^{*\neg RJV})^2 = \Delta_{RJV}(\Delta_{RJV} + q_k^{*\neg RJV}). \tag{2.24}$$

Take two sequential firms $i = N - 1$ and $j = N$ such that $\eta_i < \eta_j$. In equilibrium $q_i^{\neg RJV} > q_j^{\neg RJV}$. Therefore, equation (2.24) implies that

$$(q_i^{*RJV})^2 - (q_i^{*\neg RJV})^2 > (q_j^{*RJV})^2 - (q_j^{*\neg RJV})^2 \Rightarrow \phi_i > \phi_j. \tag{2.25}$$

Specifically, $\phi_i - \phi_j = \frac{\nu(\eta_j - \eta_i)}{(1+N)\beta} = q_i^* - q_j^*$. Therefore, firm j will enter the RJV for all entry costs $\phi_j \in [0, \Delta_{RJV}(\Delta_{RJV} + q_j^{*\neg RJV})]$ and will not enter if the actual entry cost $\Phi > \Delta_{RJV}(\Delta_{RJV} + q_j^{*\neg RJV})$. Firm i will enter the RJV if the entry cost $\phi_j \in [0, \Delta_{RJV}(\Delta_{RJV} + q_j^{*\neg RJV}) + \frac{\nu(\eta_j - \eta_i)}{(1+N)\beta}]$. Proceed by induction until arriving at firm 1 where $\phi_1 \in [0, \Delta_{RJV}(\Delta_{RJV} + q_j^{*\neg RJV}) + \frac{\nu(\eta_N - \eta_1)}{(1+N)\beta}]$. Thus, for any enter fee

$$\Phi \in \left(\Delta_{RJV}(\Delta_{RJV} + q_j^{*\neg RJV}), \Delta_{RJV}(\Delta_{RJV} + q_j^{*\neg RJV}) + \frac{\nu(\eta_N - \eta_1)}{(1+N)\beta}\right) \tag{2.26}$$

there will be a firm h such that all firms with costs lower than firm h enter and all firms with costs higher than firm h do not, giving the desired result.

Proposition 2:

For any market size N in which a private RJV is productive and is rationalizable by at least two firms $n < N$, there is a convex set in parameter space (marginal productivity of R&D, range of idiosyncratic costs and RJV entry costs) such that the members already in the RJV will exclude any additional members. The size of the RJV needed to block further entry is increasing in the productivity of R&D and the size of idiosyncratic costs relative to shared industry costs and decreasing in RJV entry costs.

Consider the expected change in profits to a firm i that is a founding member of a RJV caused by increasing the number of RJV members by one. Treating n as a continuous variable, the chain rule implies that $\frac{\partial \pi_i^*}{\partial n} = 2q_i^* \frac{\partial q_i^*}{\partial n}$. Given that cournot quantities are always positive, the entire expression's sign is a function of $\frac{\partial q_i^*}{\partial n}$, which allows it to be worked with independently. Working with the derivitive of quantity with respect to RJV size n directly, we find the derivitive can be expressed as

$$\frac{\partial q_i^*}{\partial n} = \frac{-v\frac{2k(P-\bar{c})^2}{\Phi((n+1)(n+2))^2}(2n+3) - \bar{c} + Nv\frac{2kn(P-\bar{c})^2}{\Phi((n+1)(n+2)n)^2}(3n^2+6n+2)}{(N+1)\beta}. \tag{2.27}$$

Whenever equation (2.27) is greater than zero, firm i will prefer an addition firm to enter. Rearranging terms, equation (2.27) is greater than zero if

$$\frac{N(3n^2+6n+2) - 2n^3 - 3n^2}{((n+1)(n+2)n)^2} > \frac{\bar{c}\Phi}{k(P-\bar{c})^2}. \tag{2.28}$$

All the terms that comprise the right hand side of equation (2.28) are positive parameters and the derivative of the right hand side with respect to any of the parameters is continuous and monotonic. The derivative of the left hand side of equation (2.28) with respect to n is always negative so that the relative benefit of adding another firm the RJV is always falling and for any $n < N$, the left hand side of equation (2.28) is positive. For an industry size N, the limit of the left hand side of equation (2.28) as $n \to N$ is $\frac{N^3+3N^2+2N}{((N+1)(N+2)N)^2}$ which is a positive number and the limit as $N \to \infty$ is zero. Therefore, for every industry size N and every $n < N$ there is a convex subset of parameter space $\{\bar{c}, P, k, \Phi\} \in \Theta$ such that existing members of the RJV will prevent other members from joining.

By inspection, the right hand side of equation (2.28) is decreasing in both k and $(P - \bar{c})$ and increasing in Φ. Using the result from above that the left hand side is decreasing in n for all N, the final result in established.

Corollary 1:

An exclusive RJV that includes a national lab with exogenous funding will always have fewer members than a RJV which includes a national lab but doesn't have exogenous funding.

Include a fixed funding component representing a direct subsidy to a RJV project. Using equation (2.28), rewrite the equation to include a direct subsidy for each firm to a RJV defined as F:

$$\frac{N(3n^2+6n+2)-2n^3-3n^2}{((n+1)(n+2)n)^2} > \frac{\bar{c}(\Phi+F)}{k(P-\bar{c})^2}. \tag{2.29}$$

So long as F is positive the right hand side of equation (2.29) is greater than the right hand side of equation (2.28). As a result, the inequality defines a large RJV size n since the left hand side of equation (2.29) is strictly decreasing in n giving the desired result.

Corollary 2:

Exclusive RJVs without funding but including national labs will be larger than RJVs without funding and without national labs if RJVs excluding labs have on average 1) higher entry fees Φ, 2) lower productivity k or 3) are selected by firms closer to each other in technology space ($P - \bar{c}$ small).

Consider the implicitly defined size of exclusive RJVs that both include and exclude National Labs. By the monotonicity of the left hand side of equation (2.29), if parameters can vary between projects and the average size of exclusive RJVs that include national labs is greater than those that don't, it must be that:

$$\frac{\bar{c}(\Phi)}{k(P-\bar{c})^2} > \frac{\bar{c}_{RJV}(\Phi_{RJV})}{k_{RJV}(P-\bar{c_{RJV}})^2} \tag{2.30}$$

By inspection, the corollary must be true for exclusive RJVs for the first and second claim. Given that technology space maps to cost space monotonically, the claim is true for the third claim.

Chapter 3

Uncertainty in the Relationship Between Emissions and Ambient Pollution Levels and Optimal Pollution Control

Abstract

The standard economic theory of pollution control is premised on the manifestly false assumption that all sources of pollution emissions are known. In Los Angeles, the most studied location in the world for air pollution, it was recently discovered that over 10% of several regulated air pollutants were coming from a previously unknown source, large ships in the Los Angeles Harbor. The science of greenhouse gases presents a seemingly endless stream of such discoveries. The fundamental source of the problem is the ability to observe pollution emissions from specific sources, the ability to measure ambient pollution levels, and the ability to use of scientific models to calibrate the observed emissions to observed ambient levels. This paper considers the implications on optimal pollution control when ambient levels of pollution are known but all emission sources are not. The model shows that if the dispersion models are misspecified due to incomplete inventories of emissions, optimal ambient pollution levels can actually increase. In this case, if R&D can increase the set of known emitters, a regulator may actually choose not to spend any resources to do as it can cause a decrease in expected

welfare.

3.1 Introduction

There is considerable interest in knowing the precise relationship between emissions and ambient pollution levels in order to develop efficient pollution regulation. As long as the relationship between emissions and ambient pollution is known, uncertainty is limited to either the damages associated with a given level of ambient pollution or the costs borne by a firm of reducing emissions by a given amount. Indeed, the vast majority of the economics of pollution control literature is concerned with one of these two types of distributional uncertainty. However, if the relationship between emissions and ambient levels of pollution is itself subject to uncertainty, it can given rise to a unique set of problems for the pollution regulator.

The United States Environmental Protection Agency (EPA) utilizes both an air pollutant emissions monitoring system and an ambient air quality monitoring system to measure all air pollutants and other greenhouse gases. Controlling for other factors such as temperature, the two systems are linked to each other using an air dispersion model which takes emissions as an input affecting the stock of ambient pollution. A similar system is in place for ground water regulation. While, the potential for discord between the two monitoring systems has occasionally been noted by economists (e.g., Spence and Weitzman 1978 and Crandall 1981), its implication for optimal pollution control policies appears to be largely unexplored.

The EPA implicitly assumes that their models correctly identify the relationship between the history of emissions and current ambient pollution levels. Recent discoveries, however, show that these models can be either miss large sources of emissions needed to explain ambient pollution levels or be misspecified altogether. With respect to incomplete sets of emissions, Thiemens and Trogler (1991) show that 30% of nitrous oxide emissions are unaccounted for in emissions inventories. Similarly, Etiope and Ciccioli (2009) show that roughly 50% of methane emissions needed to explain ambient methane levels are unaccounted for.

With respect to misspecified dispersion models, it was recently discovered that ships in the LA Harbor are a significant contributor to smog, contributing between 10%-44% of ambient levels of sulfate in the LA basin (Dominguez et. al. 2008). Before the discovery, dispersion models for the LA Basin did not consider ships as an emissions source. In the 1990s, nylon production was discovered to emit large quantities of nitrous oxide, a dangerous pollutant. Upon this discovery, nylon producers voluntarily reduced their nitrous oxide emissions at very little cost. Previously, regulation forced other nitrous oxide producers to pay larger sums to abate the same amount. This type of dispersion model misspecification is not new: it wasn't until Haagan-Smit's 1951 California Institute of Technology demonstration that automobile emissions are a dominant source of air pollution in large cities.

The point to be made is that governments generally seek to reduce pollution from large sources that they know about and tend to ignore pollution that they either know that they know they don't know about (unaccounted for emissions) or don't know about altogether (dispersion model misspecification). Given the potential economic benefits of more precise synthesis of emissions and ambient pollution models, it is reasonable to expect that there are economics gains to be realized from more precise science.

This paper explores the implications of optimal pollution control policy when the regulator accounts for uncertainty in the relationship between emissions and ambient pollution explicitly. In particular, this paper examines the implications of the discovery of new sources of emissions on optimal levels of ambient pollution in addition to considering the optimal regulatory policy with emissions discovery is affected by resources dedicated to emissions research.

The model here differs from those in the existing pollution control literature in the nature of the source of the uncertainty being considered. Most of the existing models which deal with uncertainty assume that it comes from uncertainty over the damage function, uncertainty over future technologies or uncertainty from asymmetric information over costs (Weitzman 2009, Norhaus and Zang 1996, Goulder and Mathai 2000 and Lewis 1996). Uncertainty over monitoring costs has also received attention but mostly in the context of instrument choice (Schmutzler and Goulder 1997, and Millock et. al. 2002).

This paper extends the Weitzman (1974) model to show the change in optimal pollution control policy upon the discovery of previously unknown sources of emissions when 1) the marginal contribution to ambient levels of pollution of known emitters is correctly identified and 2) when the dispersion model is misspecified and the marginal contribution to ambient levels of pollution of known emitters is not correctly identified. Intuitively, if some polluters are not identified in regulators models, then status quo pollution regulation could be inefficient if there are less expensive ways to abate pollution by the unidentified polluters. However, if the model itself is misspecified, then the discovery of new sources of emissions can actually cause optimal pollution levels to increase. Essentially, if the misspecification dispersion model over estimates known emitters' contribution to ambient pollution levels and the cost of abatement newly discovered emitters' abatement function is high, such as with many newly discovered geological sources, optimal ambient pollution levels can increase.

This paper also considers the effect of allowing the regulator to dedicate resources to finding new emission sources. Not surprisingly, the ability to grow the inventory of emissions through R&D increases total welfare increases most when marginal damages are correctly identified. When marginal damages are misspecified, optimal R&D levels are higher and overall welfare is lower. Further, it is possible that accounting for misspecified marginal damages can harm overall welfare.

The remainder of the paper is organized as follows: the next section discusses the relevant literature. Section 3 both introduces the model and covers comparative statics. Section 4 offers simulations of the models and section 5 offers brief concluding remarks.

3.2 Literature Review

The economics of uncertainty in pollution regulation most often concerns uncertainty over the distribution of damages or the distribution of costs associated with any particular regulatory policy. Weitzman (1974) spawned an enormous and continually growing literature examining which policy instrument, taxes or quotas, maximize expected welfare in the presence of uncertainty over costs and finds that when marginal cost curves are steep, prices are generally a better policy instrument. Weitzman (2009) continues the analysis by questioning traditional economics analysis in the presence of fat-tailed cost distributions. While understanding the implications of distributional uncertainty is vitally important to developing optimal pollution control policy, this paper concerns a regulator's response to structural uncertainty in the relationship between emissions and ambient pollution levels.

There is significant literature addressing how a regulator should optimally respond to uncertainty over the strategic responses of regulated firms for both point source pollution (emissions from a geographically stationary source) and non-point source pollution (emissions from geographically non-stationary source). Cabe and Herriges (1992) examine non-point source pollution design under information asymmetry and Russel, et. al. (1986) examine stochastic monitoring and enforcement costs. They both find that if there is a substantial cost to monitoring ambient pollution levels or enforcing emissions, then suboptimal regulation can result, but they do not address incorrect monitoring. Both questions are relevant to the current paper in that they concern how the regulator responds to uncertainty. Notably, Segerson (1988) developed a policy mechanism for implementing a first best level of ambient pollution when regulating individual emitters is either costly or impossible. Heyes (2000) offers an excellent summary of the literature on regulation when "slippage", or lack of enforcement, occurs for a variety of reasons.

The uncertainty considered in this paper is somewhat different from uncertainty over costs or strategic responses of regulated polluters. The uncertainty here is over either the set of polluters or the estimated relationship between known emissions and ambient pollution levels. In the case where some emitters are identified with certainty, it is possible to correctly estimate the effect of changes in their emissions. For example, Chay and Greenstone (2003) and Bharadwaj and Eberhard (2008) both uses exogenous shocks to estimate the marginal effects of pollution on health outcomes. Such methodology is relevant for the model presented in this paper but most generally this paper concerns constructing regulatory policy with incorrect structural parameterizations. The structural parameters here feed into the benefit function associated with an individual firm reducing emissions to give a type of uncertainty that is novel in the environmental economics literature. Further, while there is an extensive literature on the economics of investment, there is no work addressing investment in identifying structural parameters over the estimated benefit of an individual firms contribution to public bad, as is considered here.

3.3 Model

Consider an extension of the Weitzman (1974) model of non-depletable externalities that includes structural uncertainty in the relationship between emissions and ambient pollution levels. In order to show exactly how different types of uncertainty affect the optimal pollution control problem, this section begins with the case of certainty.

Assume that each firm or industry i chooses a level of emissions, x_i to maximize profits $\pi_i(x_i)$. Assume that $\pi_i(x_i)$ is initially increasing in x and twice differentiable with $\pi_i''(x_i) < 0$. In equilibrium, each firm emits at a level x_i^* such that $\pi_i'(x_i) \leq 0$ with equality if $x_i^* > 0$.

Ambient levels of emissions y contribute negatively to social welfare according to a strictly increasing deterministic function $D(y)$. This model is unique in that ambient levels of pollution are related to emissions according to some function $y = \underline{x}'\underline{\beta} + \epsilon$ where $\epsilon \sim N(0, \sigma)$. This assumption is a generalization of the classical non-depletable externality literature in which the total amount of ambient pollution levels is the sum of emissions. This is a reasonable assumption in the case of both climate change pollutants and particulate matter as it allows for different emissions affect ambient pollution levels asymmetrically. More generally, this specification allows the implications of miscalibrated relationships between emissions and pollution levels if a subset of emission sources is not accounted for.

Assume initially that the regulator observes ambient levels of pollution and all emissions perfectly and the relationship between emissions and ambient levels of pollution is known with certainty. In this case, the regulator can construct an unbiased estimator the relationship between each polluter's emissions and ambient pollution levels. Given this specification, the relationship between emissions and ambient pollution is linear so that the OLS estimator, $\beta = \frac{y'X}{X'X}$, is unbiased.

Given these assumptions, the regulator maximizes the following objective function:

$$\max_{\{x\}} \Sigma_{i=1}^{N} \pi_i(x_i) - D(y) \tag{3.1}$$

where the conditions for optimality are

$$\pi_i'(x_i^*) = D'(y)\beta_i \ \ \forall \, i = 1, ..., N \tag{3.2}$$

In words, the N first order conditions mean that the change in profits from reducing a unit of emissions by the firm must equal the marginal damages caused by an increase in firm i's contribution the ambient pollution levels, β_i. This can be achieved via a tax or tradable quota system, assuming that a firm i's emissions can be normalized by their contribution to ambient pollution levels through β_i.

3.3.1 Uncertainty in the Sources of Emissions and Ambient Pollution

Now assume that it is possible to identify the marginal effects on health of changes in the ambient levels of pollution caused by shocks to known emitters. In this case, it is possible to identify the precise relationship between known emitters and their contribution to ambient pollution levels. The conditions for identification of the marginal effects of known emitters on ambient pollution levels include that the identification strategy is valid. In other words, the idiosyncratic shock used to identify known emitters' contribution to ambient pollution must not effect unknown emitters. Assuming that this condition is met, the marginal effect of known emitters on ambient levels of pollution can be identified.

Even if the marginal effects of known emitters is met, if there is a set of unknown emitters then a first best outcome defined by the set of equations (3.2) cannot be achieved. Rather, the best the regulator can do is to regulate known emitters at their conditionally optimal levels. In the case in which only a subset of emitters, $K < N$ are identified but their marginal effects are known with certainty, the social planner's objective function is the same as in equation (3.1), but there are only K first order conditions.

Consider the dynamics of the social planners problem if an additional emitter, $K + 1$ is discovered and that emitter's marginal effect on ambient pollution levels, β_{K+1} can be identified. There are clear welfare implications for the discovery of a new emitter: so long as the newly discovered emitter is producing as a level where $\pi'_{K+1}(x_{K+1}) < \pi'_i(x^*_i)$ for all i in the set of previously known emitters and $D(y)$ is twice differentiable, welfare must increase when the newly discovered polluter is brought under regulation. Most generally, the new emitter gives the regulator another degree of freedom to use in choosing optimal emission levels.

This situation is shown explicitly in figure 1. Upon the discovery of a new emitter j with correctly identified marginal contributions to ambient pollution β_j, the firm if forced to reduce their emissions by Δx^*_j. As the newly discovered emitter is brought under regulation, ambient pollution levels will decline by the level of their reduction, $D'(y_i - \Delta x^*_j)$. This rotates the marginal damage associated with each of the previously known emitting firm's emissions down. Therefore, while the newly discovered firm suffers from lower profits, all other firms enjoy greater profits and ambient pollution levels fall, thereby reducing damages.

This subsection has shown that welfare must increase when the marginal effects of known emitters are correctly specified and a new emitter is discovered. The next section will relax the assumption that the marginal effects of known emitters can be

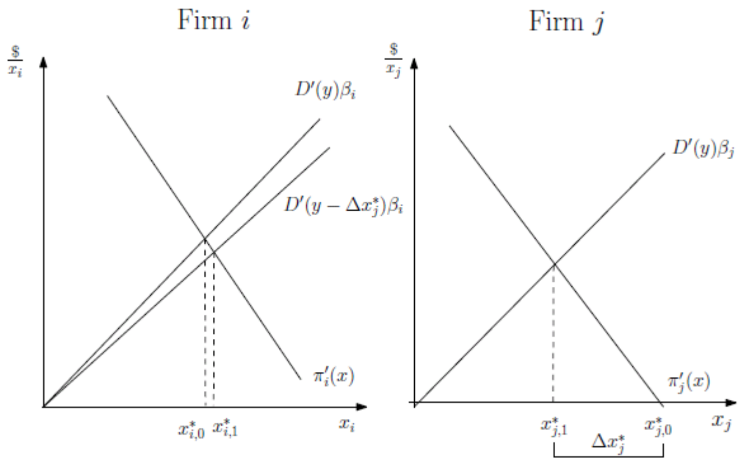

Figure 3.1: Optimal Firm Emissions Under Discovery of New Emitter

correctly identified.

3.3.2 Uncertainty in the Relationship Between Emissions and Ambient Pollution

Assume now that instead of observing all emissions x, the regulator observes only a subset of those emissions, $\tilde{x} = \alpha_0 x$ where $\alpha_0 \in (0, 1)$. For simplicity assume that the regulator observes only $\alpha_0 N$ emitters out of a total of N total emission sources. Under this assumption, if the regulator tries to estimate the contributions of observed emissions to ambient pollution levels using OLS, the estimating equation is misspecified and their estimates will be biased upward. Specifically, the estimated coefficients if y is regressed on $\tilde{X}$ take the form $\tilde{\beta} = \frac{y'\tilde{X}}{\tilde{X}'\tilde{X}} = \frac{y'X}{\alpha_0 X'X} = \frac{\beta}{\alpha_0}$.[1] The resultant optimality condition obtained from maximizing equation (3.1) in the misspecified case is

$$\pi_i'(x_i^*) = D'(y)\frac{\beta}{\alpha_0}. \ \forall\, i = 1, ..., \alpha_0 N \tag{3.3}$$

For any given y, the x_i^* implicitly defined by equation (3.3) must be lower than that implied by the optimality condition in the case with certainty given that $\alpha_0 < 1$ and that $\pi_i'(\cdot) < 0$ over the non-trivial range. The main implication for individual firms

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[1] This type of bias of the OLS estimator is a special case of multiplicative measurement error. It is relatively common in the epidemiology literature.

is that known sources are over-regulated relative to when all emissions are correctly measured because the perceived marginal damages of known emitters are higher than their actual damages.

To see this point, consider a scientific discovery reveals more emissions than were previously believed. Observed emissions are now $\tilde{x} = \alpha_1 x$ where $\alpha_1 > \alpha_0$. As a result, the estimated coefficient is $\tilde{\beta} = \frac{y'X}{\alpha_1 X'X} = \frac{\beta}{\alpha_1} < \frac{\beta}{\alpha_0}$. Given this new scientific understanding, the x_i^* implied by the new optimality condition in equation (3.3) for $i = 1, ..., \alpha_1 N$ will be lower than it was before.

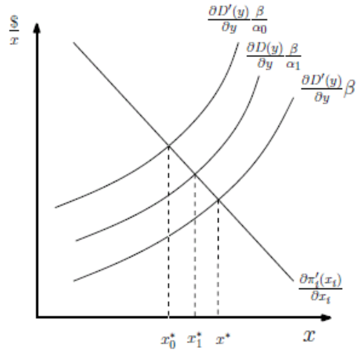

Figure 3.2: Optimal Firm Emissions Under Different α

Figure 2 shows the intuition for the above result graphically. As new emitters are discovered the perceived marginal damage of emissions curve shifts down. As a result, it is welfare improving for a firm who was emitting at level x_0 to now emit at level x_1. This example in and of itself does not imply that total ambient levels of pollution will decrease or increase after the change in the percentage of known emissions α increases. However, so long as the percentage of known emissions increases as new science informs policy, it must be the case that a previously known polluter's emissions decrease. Further, it is always weakly cheaper to achieve a given level of actual ambient pollution so long as at least one newly discovered emitter k has costs of emissions reduction less than the the highest the costs of emissions reduction to a previously regulated firm: $\frac{\partial \pi_i(x_{i,0}^*)}{\partial x} > \frac{\partial \pi_j(x_{un}^*)}{\partial x}$ where x_{un}^* is the emissions level of the unregulated firm. Put another way, an increase in the set of emitters, α, will increase the emissions of previously known emitters and decrease the emissions of a newly discovered polluter, k so long as the marginal profits with respect to emissions at the unregulated level is less than their newly perceived contribution to ambient pollution levels.

While an increase in α will make reaching any given level of actual ambient pollution weakly cheaper, it will not necessarily decrease the optimal level of perceived expected ambient pollution, $\tilde{x}\hat{\beta}$, nor the level of actual ambient pollution, $x\beta$. The discovery of the new sources may increase perceived emissions when the marginal cost of reducing emissions from previous levels for the newly discovered polluter is high and the marginal cost of reducing emissions for the previously known emitters is nearly constant. The precise conditions when ambient levels of pollution increase or decrease are related to the sign and magnitude of the second derivative of the damage function and the profit function in addition to the level of α. These conditions can be derived using Cramer's rule and can be found in the appendix.

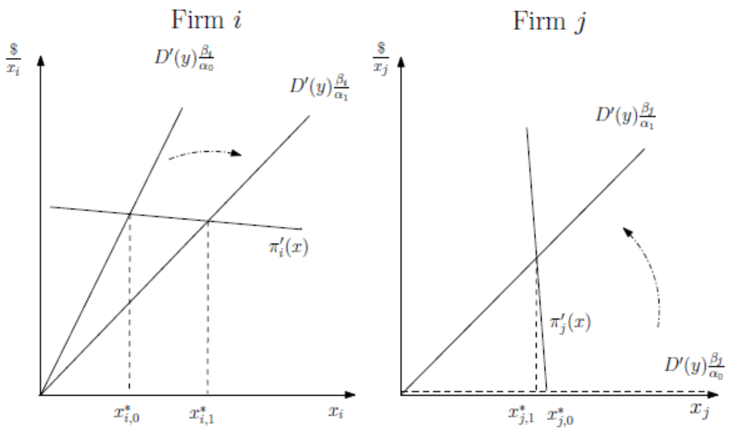

Figure 3.3: Ambient Pollution as a Function of α

The intuition can best be illustrated in a simple example illustrated in figure 3. Consider a case where there are only 2 firms i and j and that contribute to ambient pollution levels y. Initially firm i is a known emitter with equilibrium emissions of $x^*_{i,0}$ and firm j is an unknown emitter with equilibrium equilibrium emissions $x^*_{j,0}$. Upon the discovery that j is a source of emissions, the estimated damages associated with each firms emissions rotate to $D'(y)\frac{\beta_i}{\alpha_1}$ and $D'(y)\frac{\beta_j}{\alpha_1}$ for firm i and j respectively. In this example, the difference between total actual emissions before and after the new information is

$$\frac{\partial y^*}{\partial \alpha} = (x^*_{i,0} - x^*_{i,1})\beta_i + (x^*_{j,0} - x^*_{j,1})\beta_j. \tag{3.4}$$

So long as β_i and β_j are not sufficiently different in magnitude, the example shown in figure 2 will cause an increase in actual emissions. This situation might arise when a new source of emissions is discovered that can't be changed for any cost, such as the case when new emissions are part of the earth's natural processes. Such discoveries were made by Keppler et. al. (2006) and Etiope and Ciccioli (2009) when they discovered that both plants and the ocean floors may account for significant sources of methane emissions, a greenhouse gas.[2] Alternatively, if new emissions sources can be cheaply reduced, then the discovery of such new emissions source would likely reduce total ambient pollution levels.

One weakness of the approach in this section is the lack of dynamic consistency in the relationship between changes in emissions caused by the regulation of emissions and ambient levels of pollution. For example, assume that through some policy instrument a regulator reduces known emissions from $\tilde{x}$ to a level $\delta\tilde{x}$ where $\delta \in (0,1)$. In this case, expected ambient pollution will fall by $(1-\delta)\frac{\beta}{\alpha}$ but actual ambient pollution will fall by less. Over time, the regulator might account for this discrepancy in order to partially correct for biased estimates. In essence, the regulation of pollutants amounts to a natural experiment that can be used to identify parameter estimates.[3] This is a clear drawback that will be partially addressed next.

Thus far the analysis has been limited to changes in the percentage of known emissions insofar as they affect calibrated estimates of their effect on ambient levels of pollution. One reason why this is the form of the analysis is that it is impossible for the regulator to know with certainty what the new percentage of emissions, α_1, or the old percentage of emissions, α_0, actually is. Instead, the discovery only reveals the amount of new emissions discovered as a percentage of old emissions. The discovery informs the regulator of the relative change in the composition of emissions but not the level of known emissions directly.

The type of misspecification above leads to upwardly biased estimates for known

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[2] If a resource regulator sets a cap on expected ambient levels of pollution, the discovery of high cost emission sources such as those from geological processes will increase the expected cost of reach the ambient pollution level target.

[3] Note, that if there are a significant number of covariates aside from direct emissions that determine ambient pollution levels, then the dynamic consistency in estimates of marginal damages from emitters is greatly complicated.

emissions on ambient levels of pollution. This is in stark contrast to the case when marginal effects of emissions sources can be identified, but the entire set of emitters is not known.

Imagine a case that combines the two in which the regulator knows that only a subset of polluters are identified, αN, but doesn't know the size of the set of known emitters relative to actual emitters, α. further, assume the regulator cannot identify the marginal effects of known emitters. In this case of known misspecification, The regulator knows their estimates are upward biased and knows there is a set of unknown emitters of size $(1-\alpha)N$. Assume homogeneity of firms to gain intuition. As a result, optimal expected ambient pollution is $E[y^*] = \tilde{x}\frac{\beta}{\alpha_0} + (1-\alpha_0 N)x^*_{un}\beta$ where x^*_{un} is the level of emissions by unregulated sources. The resultant FOC in known misspecification regulation is

$$\pi_i'(x_i^*) = D'(y)\frac{\beta}{\alpha_0}.\ \forall\, i = 1, ..., \alpha_0 N \tag{3.5}$$

This is the same first order condition as in the previous case. Different here is that in this regulatory regime, the agency managing ambient pollution account for the known misspecification in their estimates and in the expected level of ambient pollution. As a result, this management regime is dynamically consistent and for each given level of known emitters α, equilibrium ambient pollution is different than in the case where misspecification is not accounted for.

This subsection has shown that an increase in the number of known emitters will weakly decrease the costs associated with reaching any actual or expected level of pollution. It has also shown that when new emitters are discovered the level of optimal ambient pollution may go up or down. Further, any change in the proportion of known emitters cannot be mapped with certainty to a level of emissions.[4]

Clearly, there can be significant changes in welfare associated with an increase in known sources of emissions. In the case of correctly identified marginal effects, an increase in known emissions will increase welfare and ambient levels of pollution will decrease with certainty. When marginal effects are not identified and emissions estimates are biased, an increase in known emissions will increase welfare with certainty but ambient levels of pollution can actually increase. The next section introduces an additional component to the model that allows the regulator to spend funds in order to increase α through.

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[4] In the second appendix, a Bayesian model is presented in which the regulator takes the uncertainty over the level of α into account directly and allows marginal changes in α to inform estimates of β

3.3.3 Optimal Pollution Control and Science Expenditures

This section expands the model to include the possibility that the regulator can spend resources to increase the number of known emission sources through R&D. The implications for welfare of such increased scientific expenditures are examined in the case where estimates of emissions marginal contribution to ambient pollution levels are correctly identified and when they are biased due to misspecification.

Consider the proper level of resource allocation in the case where marginal effects of known emitters are known with certainty. Trivially, the proper level of research occurs when the marginal cost of research, measured in dollars, is equal to the expected marginal benefit of research. When marginal effects are known, the expected marginal benefit of research is the probability that a new source of emissions is discovered times the benefit of discovery: reduced ambient pollution levels and the associated increase in profits with each previously known emitter. As such, when marginal effects are correctly identified the expected benefit associated with R&D is heavily dependent on three things: 1) expectations over the cost of newly discovered emitters, 2) the relative size of emissions from new sources and 3) the probability that a new emitter will be discovered.

Now consider the decision of scientific expenditures when the the relationship between emissions and ambient levels of pollution is misspecified. It was shown above that an increase in α can either raise or lower ambient pollution levels or expected social welfare. This complicates the social planner's choice of a level of resources, F, dedicated to increase the set of known emission sources. Consider the following social planner's problem:

$$\begin{aligned} &\max_{\{x\},F} \Sigma_{i=1}^{N} \pi_i(x_i) - D(y) - F, \quad y = x\beta + \epsilon \\ &\max_{\{x\},F} \Sigma_{i=1}^{N} \pi_i(x_i) - D(\tilde{x}\hat{\beta}(\alpha(F))) - F, \quad y = x\beta + \epsilon \end{aligned} \tag{3.6}$$

In this case, α is a function of funding dedicated to scientific R&D, F, and $\hat{\beta}$ is the OLS estimate of the true β as a function of α, known emissions, and ambient pollution levels. Assume that the function $\alpha(F)$ is a twice differentiable concave function of F. Given this model, the first order condition corresponding to the control variable F is

$$-D'(\tilde{x}^*\hat{\beta})\alpha'(F)\left[\frac{\partial\hat{\beta}}{\partial\alpha}\tilde{x}^* + \frac{\partial\tilde{x}}{\partial\alpha}\hat{\beta}\right] - 1 = 0. \tag{3.7}$$

Due to the misspecification that occurs from not knowing α relative to its true value and not accounting for it (unknown misspecification), both estimates of known emissions contribution toward ambient pollution levels, $\hat{\beta}$, and observed emissions, $\tilde{x}$, are functions of α and are thereby effected by changes in resources dedicated to identifying new emissions sources. As shown earlier, it must be the case that $\frac{\partial \hat{\beta}}{\partial \alpha}$ is less than zero for previously known emitters. In order to have an interior solution, the change in emissions from known emitters caused by an increase in alpha, $\frac{\partial \tilde{x}}{\partial \alpha}$ must not be sufficiently positive that the term inside the bracket is positive. If the term inside the bracket is positive then the regulator chooses to spend no resources on finding new emitters.

Alternatively, when the misspecification is accounted for by the regulator, the FOC corresponding to the control variable is

$$-D'(\tilde{x}^* \hat{\beta})\alpha'(F)\left[\frac{\partial \hat{\beta}}{\partial \alpha}\tilde{x}^* + \frac{\partial \tilde{x}}{\partial \alpha}\hat{\beta}\right] - N x_{un}^* \beta - 1 = 0. \tag{3.8}$$

The additional term signifies that as more emissions are identified, there is an additional benefit to less biased estimates of marginal effects: the new sources reduce their emissions from previously unregulated levels x_{un}^*.

The implications for this finding are stark: if the model linking emissions to ambient levels of pollution is misspecified it is possible for expected welfare to decrease if new sources of emissions are discovered that have a high cost of abatement. As such, a social planner with a misspecified social welfare function would choose not to invest resources in discovering such sources of emissions, like those from naturally occurring geological processes, because expected welfare would decrease.

This section has shown the nature of social planner equilibria in choosing the level of emissions under three different scenarios: the case of certainty in the relationship between emissions and ambient levels of pollution, uncertainty over the set of polluters but certainty in the effect of marginal emissions, and two types of misspecification in the relationship between emissions and ambient pollution. The role of costly research to increase knowledge over the set of known polluters was also considered. More concrete analytical analysis than that which is presented here is both complex and not entirely intuitive due to the highly endogenous nature of this problem. In order to provide intuition, the next section simulates the model presented in this section for optimal management for each type of uncertainty considered above.

3.4 Simulation

This section parameterizes the model presented in section 3 to show the different equilibria that can result under different management and uncertainty scenarios: Full information, no regulation, correctly identified partial . Assume that α_0 is the initial percentage of total emitters N that are known. Consider the follow set of functional forms in order to parameterize the above model:

- $\pi_i(x_i) = ax_i - \frac{b}{2}x_i^2 \;\; \forall\, i = 1, ..., N$
- $D(Y) = \frac{c}{2}Y^2$
- $\alpha(F) = \alpha_0 + (N - \alpha_0)(1 - e^{-\lambda F})$
- $y = \Sigma_i^N x_i + \epsilon$

Given these functional form assumptions, we can perform comparative static exercises for various parameterizations of the model. Note that all marginal effects of emitters are unity and that firms are homogeneous. Homogeneity of firms allows simple characterizations of equilibrium by the use of symmetry. For simplicity, assume large samples are used when estimating the marginal effects of emissions on ambient levels of pollution.[5] The welfare function implied by these assumptions is:

$$\max_{\{x\},F}(N\alpha(F))\pi_i(x_i^*) + (N(1-\alpha(F)))\pi_i(x_{un}^*) - D(\tilde{x}\hat{\beta}(\alpha(F))) - F. \tag{3.9}$$

In equation (3.9), the term x_{un}^* refers to the level of pollution for an unregulated firm.

Table 1 and figure 4 summarize the set of equilibria for in each of the different management scenarios presented in the previous section. In addition to showing the closed form solutions for emissions as a function of underlying parameters, table 1 ranks each type of management regime by optimal R&D level and welfare at the optimum for a given set of parameters. Figure 4 shows welfare as a function of R&D spending.

The full information case provides an upper bound for welfare and the unregulated case provides a lower bound. When there is known misspecification in the estimates

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[5] Actual estimation exercises were performed on simulated data and provide the exact same intuition. When sample sizes are small, the same results hold on average for Markov Chain Monte Carlo simulations, but the is significant noise.

Table 3.1: Equilibria Characterizations Under Different Uncertainty and Management Options

	Equilibrium Emissions (x_i^*)			
	Known Emitters	Unknown Emitters	R&D Rank*	Max Welfare Rank*
Unregulated	$\frac{a}{b}$	$\frac{a}{b}$	5	5
Full Information	$\frac{a}{b+Nc}$	NA	5	1
Correctly Identified ME	$\frac{a-c\left[(1-\alpha)N\frac{a}{b}\right]}{b+\alpha Nc}$	$\frac{a}{b}$	3	2
Known Misspecified ME	$\frac{a-c\left[(1-\alpha)N\frac{a}{\alpha b}\right]}{b+Nc}$	$\frac{a}{b}$	2	3
Unknown Misspecified ME	$\frac{a}{b+Nc\frac{1}{\alpha}}$	$\frac{a}{b}$	1	4

* = When parameterized such that $b > a$. ME = Marginal Effects.

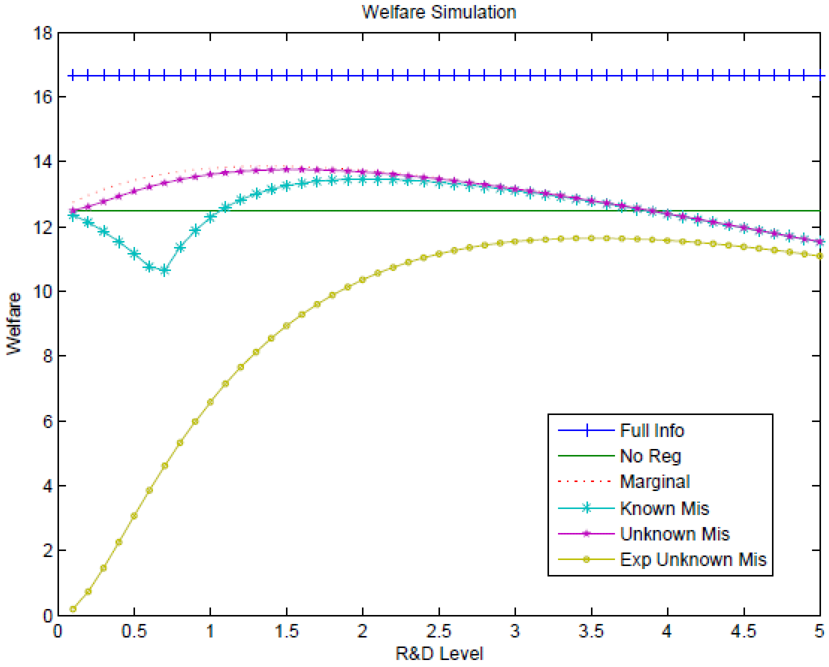

Figure 3.4: Welfare Under Different Types of Uncertainty. $a = 1,\ b = 2,\ c = .01,\ \lambda = .6,\ N = 100, \alpha_0 = 0$

of known emissions, suboptimal levels of R&D spending can actually decrease welfare relative to the unregulated case. When there is known misspecification, the estimated marginal damages of identified emitters are high enough to shut down the firm entirely. At a some level of R&D, .6 in this parameterization, the benefit of increased R&D becomes positive since estimates of marginal damages are less biased and the set of known emitters grows, defraying abatement costs and increasing profits of known emitters. Intuitively, optimal R&D spending is the highest in this regime due to the benefit of less biased estimates of marginal damages of identified polluters caused by having more knowledge about the set of polluters.

When marginal effects are correctly identified, R&D expenditures are the lowest and welfare is the highest. The benefit of additional R&D in this management regime is exclusively through the decrease in ambient levels as there is no over regulation on firms known to emit as in the case of known misspecification. As such, the marginal benefit of increased R&D is lower than the other two management regimes.

When marginal effects are misspecified and the misspecification is unknown, how R&D affects both expected welfare ("Exp Unknown Mis") and actual welfare ("Unknown Mis") must be considered. Expected welfare is what the regulator optimizes over and shall be considered first. There are two effects that are caused by an increase in R&D funding. There is the direct effect on actual welfare from reduced actual ambient pollution through an increase in R&D funding. Given this type of misspecification, expected ambient pollution ,$\tilde{x}\hat{\beta}$, is incredibly responsive to small changes in known emissions. As a result, while there is heavy regulation of known polluters for low levels of α, there is a large benefit to increasing R&D on expected ambient pollution reductions. In addition, a larger α also defrays abatement costs to known emitters. However, since in the unknown misspecified case the regulator does not account for profits or emissions from unknown emitters, they select a level of R&D that is too high and produce an actual level of welfare that is lower than if they had implemented this management regimes emissions targets at a lower level of R&D.

3.5 Conclusion

This paper shows the implications of accounting for uncertainty in the relationship between emissions and ambient levels of pollution. The type of structural uncertainty modeled here is different than the distributional uncertainty typically addressed in the literature. The model shows that the discovery of new emitters will always lower optimal ambient pollution in the case where the influence of marginal emissions on ambient pollution levels are correctly specified. In this case, research aimed at increasing the set of known emitters always improves welfare. Conversely, if marginal emissions are misspecified it is possible for optimal ambient pollution levels to increase if marginal emissions are overestimated and newly discovered emissions have a high cost of abatement.

When R&D is linked to known emissions levels, the form of regulatory response to uncertainty in the set of emission sources is important for the selection of R&D levels and overall welfare. When the effect of marginal emissions on ambient pollution is correctly identified, R&D levels are lowest because the benefit of addition R&D is limited to decreases in ambient pollution. When marginal effects are misspecified, there is an additional effect on increased profit for firms that were previously regulated at inefficient levels. As such, equilibrium R&D is higher when marginal effects of emissions are misspecified.

There are several implications for the second finding. First, if known emitters are over-regulated due to misspecification of the dispersion model, it implies that firms have an incentive to find new sources of emissions, especially high cost sources such as those deriving from geological processes.[6] Second, the regulator has an incentive to invest in the discovery of anthropogenic emissions that are presumably lower costs. Third, it is always best for known emitters to identify their marginal contributions to ambient levels of pollution if the dispersion model is misspecified.

There are several drawbacks to the modeling approach presented in this paper. The model of dispersion misspecification is not dynamically consistent when emissions uncertainty is unknown. There is, however, evidence that actual calibration processes used by environmental regulatory agency are not consistent: depletion of the stratospheric ozone layer by chlorofluorocarbons was predicted by Rowland and Marino in 1974, well before its confirmation in 1985 by a British satellite which had been previously recalibrating its instruments to ignore the hole in the ozone.

Finally, while there is a protocol in the US EPA and other OECD countries' environmental agencies for updating policy in response to scientific discovery, the EPA does not account for scientific uncertainty directly in their regulatory decisions. For

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[6] If pollution is regulated with a safety standard as opposed to optimally, this will definitely not be the case.

example, actual baseline emissions levels are difficult if not impossible to know with certainty however they are assumed to be known with certainty. The Baysesian modeling approach introduced in the appendix is perhaps the most intriguing way forward in being explicit about how pollution regulators can endogenize scientific uncertainty in their pollution control policies and merits future research.

I happily acknowledge Richard Carson's coauthorship on this chapter of this dissertation.

3.6 Appendix

3.6.1 General Conditions for Changes in Emissions as a Function of α

This appendix shows precisely how a change in known emissions will affect optimal ambient pollution levels in a very general framework. The objective function of the regulator in this model is

$$\max_{\{x\}} \Sigma_{i=1}^{N} \pi_i(x_i) - D(y).$$

where $E[Y] = x'\beta + \epsilon$ and x is the N x 1 vector of emissions. Differentiating this equation with respect to the N control variables gives the N first order conditions needed for optimality that implicitly define the set of optimal emission levels $\{x^*\}$. Totally differentiating each first order conditions with respect to the parameter of interest α the coefficients on $d\alpha$ must be equal to zero. Applying Cramer's rule to the system of equations, the derivative of the equilibrium value of a control variable x_i^* can be written as

$$\frac{\partial x_i}{\partial \alpha} = \frac{|\Lambda_i|}{|H|} \tag{3.10}$$

where H is the Hessian of the objective function and Λ is the Hessian matrix with the ith column removed and replaced with the vector of the negative of all first order conditions differentiated with respect to α. By the second order conditions for welfare maximization, $|H| > 0$. Given this set-up, the change in equilibrium ambient levels of pollution y^* with respect to α is

$$\begin{aligned}
\frac{\partial y^*}{\partial \alpha} &= \Sigma_i \left(\frac{|\Lambda_i|}{|H|} \hat{\beta}_i + \tilde{x}_i^* \frac{\partial \hat{\beta}_i}{\partial \alpha} \right) \\
&= \Sigma_i \left(\frac{|\Lambda_i|}{|H|} \frac{\beta_i}{\alpha} + \tilde{x}_i^* \left(-\frac{\beta_i}{\alpha^2} \right) \right) \qquad (3.11) \\
&= \frac{1}{|H|} \Sigma_i \hat{\beta}_i \left(|\Lambda_i| - x_i \right) \qquad (3.12)
\end{aligned}$$

The interpretation of (3.12) is that the change in ambient pollution as a function of α depends on the sign of the change in observed emissions relative to the magnitude of the changes in known emitters caused by a change in α.

3.6.2 A Bayesian Approach to Emissions Uncertainty

Given that this model allows for changes in α, a dynamically consistent regulator should take this the uncertainty over α into account when they design optimal policy. Specifically, the resource regulator can account for uncertainty over α explicitly in their estimation procedure. Consider a case in which the regulator models alpha as a random variable and observed emissions, $\tilde{x} = \alpha x$ as true emissions suffering from a type of measurement error where the error term is bound above by 1 and below by zero, $\alpha \in (0, 1)$. If α was known then the true β for known emitters could be measured with certainty and they could be regulated fairly. Further, assume that the regulator has a prior over α and the vector of emissions coefficients $\underline{\beta}$. Given these assumptions, the regulator can estimate the relationship between emissions and ambient pollution levels in a Bayesian framework.

In order to address the regulator's problem, the econometric problem must be introduced first. Assume that the prior distribution for β is $\pi(\beta) = N(\beta_0, B_0)$.[7] In order to provide intuition, it is useful to first construct the Bayesian estimator of β as a function of $\tilde{x} = \alpha x$ ignoring the uncertainty over α. In this case, the posterior distribution of the coefficients on emissions is $\pi(\beta|y) \propto N(\bar{\beta}, B_1)$ where the updated parameters are $B_1 = (\tilde{X}'\tilde{X} + B_0^{-1})^{-1}$ and $\bar{\beta} = B_1(\tilde{X}'y + B_0^{-1}\beta_0)$. Substituting the definition of $\tilde{X}$, the updated parameters can be rewritten as $B_1 = (\alpha^2 X'X + B_0^{-1})^{-1}$ and $\bar{\beta} = B_1(\alpha X'y + B_0^{-1}\beta_0)$. In essence, the multiplicative error of this form cause more weight to be put on the data than would otherwise be causing the mean of the

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[7] To highlight the effect of uncertainty over α, a prior over the variance of ϵ is not considered here. Note, though, that if one wanted to use the data to inform the prior over σ_ϵ then the uncertainty over α must be taken into account.

posterior, $\bar{\beta}$, to move toward the data too quickly. As weight on the prior falls to zero, the multiplicative errors cause the mean of the posterior, $\bar{\beta}$, to be too high as is the case of OLS.

In order to account for the uncertainty over α, assume that the regulator has a beta prior over α such that $\pi(\alpha) \propto \alpha^{(\rho-1)}(1-\alpha)^{(\phi-1)}$. The corresponding prior mean is $E(\alpha) = \frac{\rho}{\rho+\phi}$. Assume that the true relationship between emissions and ambient levels is $y = x'\beta + \epsilon$ where $\epsilon \sim N(0,1)$ for simplicity. If only $\tilde{x} = \alpha x$ is observed then we can rewrite the relationship as $y - \tilde{x}'\frac{\beta}{\alpha} = \epsilon \sim N(0,1)$. In this rewritten form, the likelihood function is proportional to the following expression:

$$f(y|\alpha,\beta,) \propto \exp\left(-\frac{1}{2}\left(y - \tilde{x}'\frac{\beta}{\alpha}\right)'\left(y - \tilde{x}'\frac{\beta}{\alpha}\right)\right). \tag{3.13}$$

Given the earlier assumptions, then, the full posterior distribution is proportional to

$$\begin{aligned} f(\alpha,\beta,|y) &= f(y|\alpha,\beta,)\pi(\beta|\alpha)\pi(\alpha) \\ &\propto \exp\left(-\frac{1}{2}\left(y - \tilde{x}'\frac{\beta}{\alpha}\right)'\left(y - \tilde{x}'\frac{\beta}{\alpha}\right)\right)\exp\left(-\frac{1}{2}\frac{(\beta-\beta_0)^2}{B_0}\right) \\ &\quad *\alpha^{(\rho-1)}(1-\alpha)^{(\phi-1)}. \end{aligned} \tag{3.14}$$

Equation (3.14) shows that deriving full conditional posterior distributions to be used in Gibbs sampling estimation for generating distributions of β and α is impossible because of the quotient terms in them likelihood function. As such, Metropolis-Hastings (MH) sampling procedures must be performed to derive the distribution of the β and α terms.

Remembering that the goal of analysis in this section is to show how the inclusion of explicit uncertainty affects estimates of β and how that estimate affects optimal pollution control. Once the MH procedure gives the regulator distributions of the parameters of interest, the regulator can take the mean or the median of those distributions to assign optimal levels of emissions and, therein, affect ambient pollution levels. Note that only when there is a known change in α with the prior over alpha be updated.

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