Sequential Game Framing of Ambient Tax for Non-point Source Pollution

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Abstract

Ambient taxes offer a promising alternative to ameliorate the problem of non-point source pollution. Such taxes can induce polluters to collectively meet the pollution standard at least cost under certain settings. But in other possibly more realistic settings, it may achieve the pollution standard at higher than least cost if not at highest cost. This result is due to the presence of free-riding incentives and I show in this paper the conditions in which uncertainty about firm types may lead to incorrectly setting the uniform ambient tax rate which then creates free-riding incentives. I also show how the Nash and Sub-game Perfect Nash equilibria diverge in such cases. The main result is that the SPNE is unique, regardless of the value for t and produces a compliance outcome but at the higher than least cost.

Introduction

Much of the environmental economics literature focuses on policies that are based on observed individual emissions such as Pigouvian taxes, tradable permits, and even Coasian bargaining mechanisms. However, there is an entire class of pollution problems that render individual emissions monitoring infeasible or prohibitively costly due to the sources of pollution being diffuse and/or the emissions transfer function being stochastic. Such occurrences are referred to as non-point source (NPS) pollution.

In the U.S., NPS pollution problems represent the last major hurdle to achieving water quality goals with agricultural runoff as the main source of such pollution (U.S. Environmental Protection Agency, 2016). Due to the unobservable nature of NPS pollution, traditional emissions based policies cannot be applied. Fortunately, there are many alternatives in the policy toolbox from which to choose. There are input based policies, emissions proxies, and ambient quality based policies. Of the three, policies based on emissions proxies seem to be benefiting the most with advancements in monitoring technologies. However, my understanding is that such advancements have yet to materialize for water pollution problems. As such, emissions proxy based policies still suffer from the problem of inaccurate estimation of individual emissions for which policy is to be based on.

Basing policies on observable ambient quality can overcome many of the issues with the other two alternatives. First, it gives incentives to abate and is flexible in regards to the method of abatement, unlike input taxes. Secondly, ambient based policies are based on observables rather than estimates of emissions making it more parsimonious and accurate. However, ambient based policies come with problems as well. Namely, how to achieve first-best outcomes when individual emissions is not observable?

Segerson (1988) and Meran and Schwalbe (1987) were the first to suggest ambient based policies to correct for NPS pollution and showed how an ambient tax/subsidy can induce polluters to collectively choose the socially optimal level of ambient concentration as a Nash Equilibrium. However, their proposed solutions involve charging firm specific tax rates which requires knowledge of firms' abatement cost functions thus placing an informationally expensive burden on the regulator. If knowledge about the distribution of types is available, it is possible to achieve first best abatement allocations with a uniform tax rate even with heterogeneous firms (Segerson and Wu, 2006). Without such information readily available, the regulator has two options. First, a damage based tax can be implemented according to Hansen (1998) which only requires knowledge about the damage function at the socially optimal ambient level. Alternatively, Segerson and Wu (2006) develops a regulatory threat mechanism whereby the regulator threatens the NPS polluters with an ambient tax if polluters don't achieve the standard voluntarily. The ambient tax, if implemented, requires the regulator to invest resources to learn about the firm types in order to optimally set the tax rate.

Any informational requirement about the damage function or distribution of firm types is, in practice, still a significant hindrance for the regulator. Hansen (1998) briefly discusses the possibility for the regulator to initially set a very low uniform tax rate and ratchet it up until compliance is achieved. Under a setting with no collusion, this process does have appeal for feasibility reasons. However, this allows the possibility of incorrectly setting the uniform tax rate. Thus one major goal of this paper is to explore the consequences of setting a uniform tax rate that is too high given the regulator's goal of compliance. The reason why the focus is on setting the rate too high is because I am primarily interested in compliance outcomes; if the rate were too low then a compliance outcome is not possible under our context.

I find that when the uniform tax rate is set too high relative to the ambient standard, then the possibility of achieving compliance at greater than least cost arises. This occurs because when the tax rate is set too high, a multiplicity of NEs arise where strategies are abatement decisions. These NEs, aside from the socially optimal point, creates a situation where free riding behavior is allowed to co-exist with a compliance outcome consistent with Kotchen and Segerson (2020). This is because in the presence of under abatement (relative to what is socially optimal) by some, other polluters will find it more profitable to over abate and achieve compliance rather than abate at their socially optimal level leading to noncompliance and thus incurring a tax penalty. This is the fundamental moral hazard problem prevalent in team games giving rise to free-riding behaviors (Holmstrom, 1982). However, if the regulator sets the uniform tax rate "perfectly" given the compliance goal, then polluters would never find it more profitable to over abate to achieve compliance given the presence of under abatement from others.

The other main contribution of this paper is to analyze the Subgame Perfect Nash Equilibrium (SPNE) as an alternative yet important equilibrium concept for the application of an ambient tax. Many water quality goals encompasses rivers/streams which have a flow direction dictated by gravity which allows the possibility of differential "power" among polluters based on their river location. This idea has been studied in the literature on irrigation access as a public good (Bell et al., 2015; D'exelle and Lecoutere, 2012) and has recently been studied in a NPS pollution context by Zia et al. (2020). Though in their model, the differential strategies between players located more upstream and those more downstream arises because of the differences in nutrient transport, specifically the process of nitrification. It is important to understand whether upstream players and downstream players have a power differential even in the absence of heterogeneous transport.

A broader point can be made that in dynamic contexts, the SPNE is always the more plausible solution concept since it filters out NEs that reside on the off equilibrium paths and thus have no credibility. In the context of this paper, the dynamism occurs over space rather than time. However, I do not contend that the SPNE is the correct concept instead of the NE concept in situations with water flow. Rather, both concepts serve as useful benchmarks with which to evaluate real life applications of ambient policies. Such real world contexts likely fall somewhere in between a purely simultaneous game and a purely sequential game. Aside from Zia et al. (2020), the literature on NPS pollution has largely ignored the other useful extreme, that is the pure sequential game. This paper shows that the SPNE produces an important and interesting prediction that is different from the Nash Equilibrium which is traditionally used in the literature.

There are many other issues with ambient policies that is not addressed in this paper. For instance, efficacy of ambient policies requires firms to understand that their actions have effects on measurable ambient quality. This is typically only an issue when the number of polluters is large and thus ambient policies have much greater appeal in settings with few polluters. However, settings with few polluters could exacerbate the collusion issue that can arise under ambient policies (Cabe and Herriges, 1992). Collusion occurs when polluters have the ability to communicate with each other and find it collectively more profitable to over abate at the aggregate level. This paper abstracts away from the collusion issue by focusing on a pure ambient tax which gives no subsidies for over abatement. Combining this with the assumption of no stochasticity in the ambient quality results in no incentive to collude and over abate. This result is confirmed in the experimental literature on ambient policies for NPS pollution (Cochard, Willinger and Xepapadeas, 2005).

Section 1 will provide the model setup. Section 2 will provide results.

Model Setup

Consider n known polluters (firms) whose discharge all go to the same monitoring point. Firms differ in location and are all situated along a simple linear river network and for now, are allowed to be heterogeneous. I allow firms to freely choose their discharge level (X_i) and I abstract away from both output decisions and the consumer market. Pollution is diffuse so that the regulator cannot feasibly monitor individual discharge levels. Figure 1 depicts a two player example of the game tree.

The regulator observes ambient quality X each period, takes the ambient standard $\overline{X}$ as given and chooses a value for the uniform tax rate t that will induce a compliance outcome. Each firm faces an ambient tax policy given by

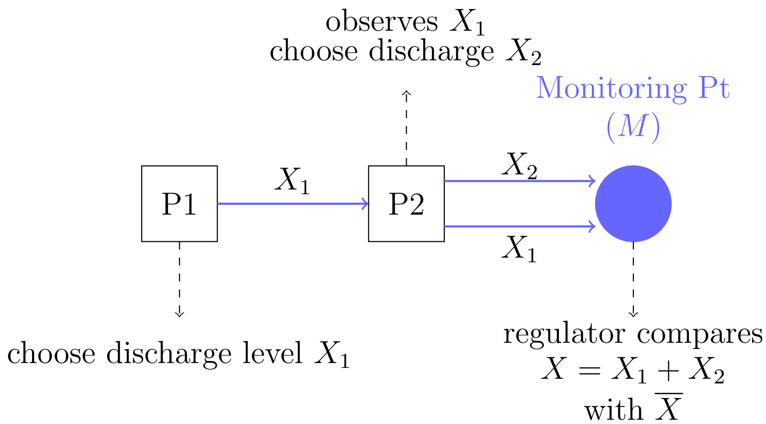
$$T_i(X) = \begin{cases} 0 & \text{if } X \leq \overline{X} \\ t(X - \overline{X}) & \text{if } X > \overline{X} \end{cases} \tag{1}$$

Denote t^* as the minimal tax rate value that can support a compliance outcome as an NE. Then since it is assumed that the regulator iteratively adjusts t until a compliance outcome is achieved, then we know for sure that $t \geq t^*$. Firm level payoffs are given by

$$\Pi(X_i, X, \theta_i) = \begin{cases} \pi(X_i, \theta_i) & \text{if } X \leq \overline{X} \\ \pi(X_i, \theta_i) - t(X - \overline{X}) & \text{if } X > \overline{X} \end{cases} \tag{2}$$

where $\pi()$ is the farm profit for a chosen individual pollution level without tax burden considerations. Firm types are given by θ_i and $\pi_i(X_i)$ is short hand for $\pi(X_i, \theta_i)$. A higher value for θ is assumed to have a positive effect on the marginal profit of pollution ($\frac{\partial^2 \pi_i}{\partial X_i \partial \theta_i} \geq 0$) and thus leading to a higher level for X_i^{bau}. I further assume that, in the absence of any regulation, the business as usual level of discharge is X_i^{bau} for each firm. The ambient pollution is the sum of discharges across all polluters $X = \sum_{j=1}^{n} X_j$. Lastly, $\pi_i(\cdot)$ is assumed to be an upside down parabola where $\pi_i'(X_i^{bau}) = 0$ and $\pi(0) = 0$.

Figure 1: 2 Player Example Model



The Social Planner

The regulator understands that this is a NPS pollution problem and that an ambient tax will induce a strategic game among the polluters. The goal of this section is to pin down the optimal uniform tax rate. The planner wants to choose pollution allocations $(X_1, \ldots, X_n)$ so that ambient quality reaches the standard $(X \leq \overline{X})$ at least cost. The cost structure is subsumed in the farm profit function so that the planner problem is framed as in (3).

$$\max_{\{X_i\}_{i=1}^n} \sum_{i=1}^{n} \pi(X_i, \theta_i) \qquad \text{s.t.} \qquad X \leq \overline{X} \tag{3}$$

From equation (3), the socially optimal pollution level from individual i, denoted as X_i^*, is pinned down by (4).

$$\pi'(X_i^*, \theta_i) - \lambda^*(\theta_1, \ldots, \theta_n, \overline{X}) \leq 0 \tag{4}$$

Thus the socially optimal pollution allocation is such that everyone pollutes up to the point where their marginal profit from pollution equals the shadow price of pollution given by the lagrange multiplier, $\lambda^*(\boldsymbol{\theta}, \overline{X})$. The first best pollution allocation is then given by

$(X_1^*, \ldots, X_n^*)$.

Firm Problem

Polluting firms face the following optimization problem

$$\max_{X_i} \pi_i(X_i) - T(X) \tag{5}$$

where $T(X)$ is given by (1). And since the tax schedule from (1) is piecewise, solving (5) requires analyzing the optimum on both sides of the kink (see Appendix for full solution).

Proposition 0.1. *For each player i, there exists a minimum profitable pollution level (denoted as $\widetilde{X}_i$) such that player i would never find it profitable to pollute below $\widetilde{X}_i$ to avoid the tax penalty given by $t(X - \overline{X})$. The minimum profitable pollution level is indirectly given by*

$$\pi'(\widetilde{X}_i, \theta_i) = t$$

See proof on page 23.

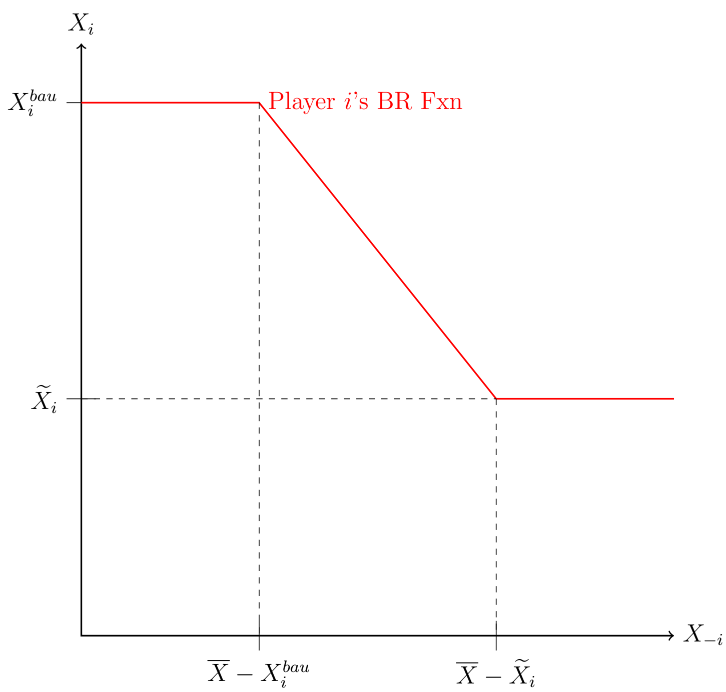
Simultaneous Game Model

Here, I present the setup for the simultaneous game by deriving best response functions and the Nash Equilibrium. From Proposition 0.1, we know that no player would choose pollution below $\widetilde{X}_i$ no matter what. Furthermore, all players would like to choose X_i^{bau} if they could without incurring a penalty. Thus for all players, their best response function given the pollution level of others (denoted as X_{-i}) is given by

$$X_i^{BR} = \begin{cases} X_i^{bau} & \text{if} \quad X_{-i} \leq \overline{X} - X_i^{bau} \\ \overline{X} - X_{-i} & \text{if} \quad \overline{X} - X_i^{bau} \leq X_{-i} \leq \overline{X} - \widetilde{X}_i \\ \widetilde{X}_i & \text{if} \quad X_{-i} \geq \overline{X} - \widetilde{X}_i \end{cases} \tag{6}$$

Equation (6) is depicted graphically in Figure 2. If player i knows that they can pollute business as usual without incurring the tax penalty then they will surely do so. However, if they cannot then they will cut back on pollution levels to avoid the tax penalty but only up to a certain point. All firms would rather contribute towards noncompliance rather than pollute below their minimum profitable pollution levels, $\widetilde{X}_i$.

Figure 2: Best Response Function for Pollution



From Proposition 0.1 and (4), we see that if the regulator sets the uniform tax rate so that it equals the lagrange multiplier λ^*, then all firms would have their minimum profitable pollution levels be equal to their socially optimal pollution levels and thus would result in a unique Nash Equilibrium where ambient quality and the pollution allocation are first best.

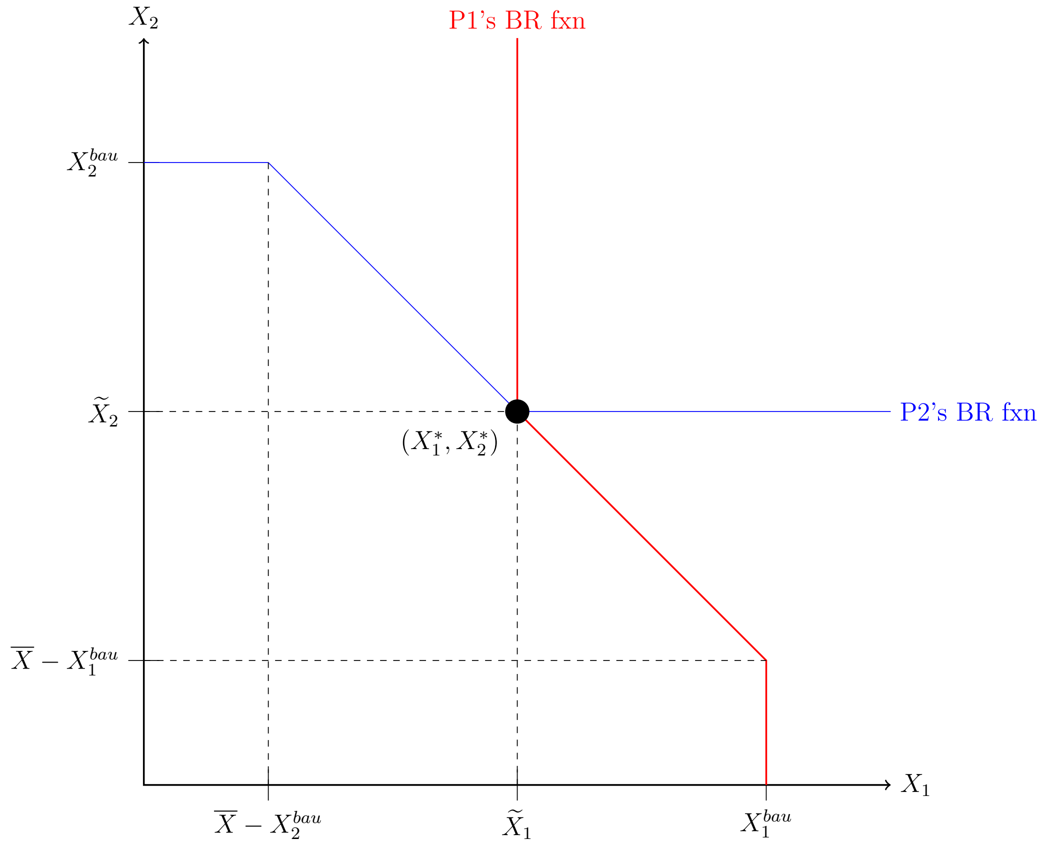
However, assuming that the regulator knows the full distribution of $\boldsymbol{\theta}$ is not likely to hold in reality. Though it could be the case that the regulator can incur a cost to learn $\boldsymbol{\theta}$, this cost could easily be prohibitively high. When $\boldsymbol{\theta}$ is unknown, it invites the possibility of having a value $t \neq \lambda^*$ while still maintaining compliance; this occurs if $t > \lambda^*$.

The Effects of t on Nash Equilibria

Here we look at the implications of various levels of t that would induce an NE on a compliance outcome. From Equation 4 and Proposition 0.1, we know that when $t < \lambda^*$, then $\widetilde{X}_i > X_i^*$ for all i since we assume $\pi'() \leq 0$. This inevitably leads to noncompliance since no one is willing to pollute below their minimum profitable pollution levels which happens to be higher than the socially optimal pollution level for each i.

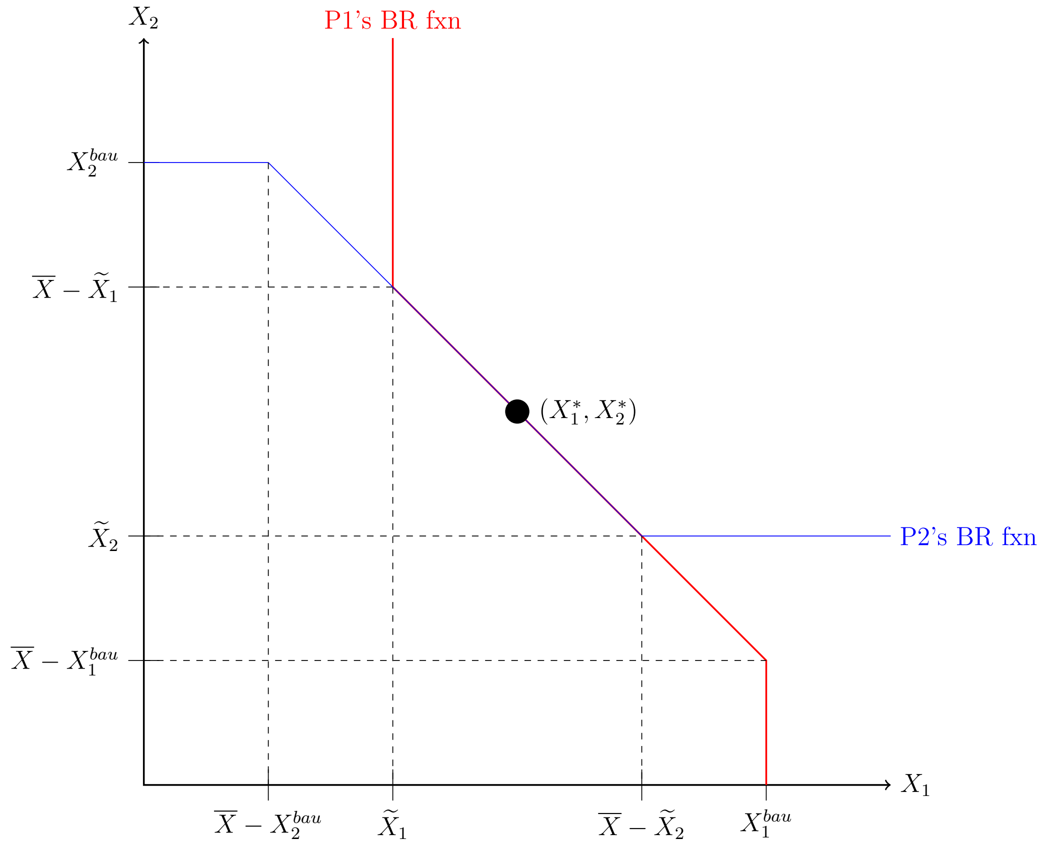
When $t = \lambda^*$, each player has their minimum profitable pollution level exactly equal to their individual socially optimal pollution level. When this happens, the only unique Nash Equilibrium pollution allocation occurs at the point where each firm pollutes exactly $\widetilde{X}_i$ as depicted in Figure 3. I refer to this value as the "perfectly" set tax rate. This choice of nomenclature captures the idea that when t is set equal to λ^*, players' best response functions intersect at exactly one point in the n-dimensional space. At that point, compliance is met exactly and at least cost to polluters.

Figure 3: Two-Player Best Response Functions (perfectly set t)



The novel result of this paper focuses attention on the case when t is set "too strictly" so that $t > \lambda^*$. This is shown in Figure 4 and when this occurs, all players' minimum profitable pollution level now lies below their individual socially optimal levels ($\widetilde{X}_i < X_i^*$). In such a setting, all firms are willing to pollute less than X_i^* but more than $\widetilde{X}_i$ to avoid a tax penalty. Therefore, some firms can get away with polluting above X_i^* and free-ride off of those who are polluting less than what is (socially) optimal. This result is a consequence of having a multiplicity of NEs where any point outside of $\boldsymbol{X}^* = (X_1^*, \ldots, X_n^*)$ is an inefficient allocation even though compliance is achieved among all the NEs.

Figure 4: Two-Player Best Response Functions (too strict of t)



Without introducing other concepts, there is no way to know which NE will be selected when $t > \lambda^*$. Worse yet, in the two player example with homogeneous types, the allocations $(X_1, X_2) = (\widetilde{X}_1, \overline{X} - \widetilde{X}_1)$ or $(X_1, X_2) = (\overline{X} - \widetilde{X}_2, \widetilde{X}_2)$ produce a compliance outcome at the highest cost.

Sequential Game Setup

Here, we try to pin down strategies of players under a sequential game and the equilibrium will be addressed later. Player 1 is the first mover while player n is the last. Following standard procedure, we utilize backward induction and first pin down the last player's strategy.

The n^{th} player's strategy is exactly described by equation (6) since they are the last mover in this game. Player $n-1$'s problem will slightly diverge from equation (6). Player $n-1$ still has the same value for their minimum profitable pollution level as in the simultaneous game. The difference here is that their compliance goal is not to stay under $\overline{X}$ since they are not the last person in the river. If player $n-1$'s goal is to reach compliance, then they must keep X_{-n} to be under $\overline{X} - \widetilde{X}_n$ because if player $n-1$ pollutes too much so that X_{-n} is too high, then player n will still choose $\widetilde{X}_n$ and thus push the group to be out of compliance. The best response function for player $n-1$ is then given by (7).

$$X_{n-1}^{BR} = \begin{cases} X_{n-1}^{bau} & \text{if} \quad X_{\uparrow(n-1)} \leq \overline{X} - X_{n-1}^{bau} - \widetilde{X}_n \\ \overline{X} - \widetilde{X}_n - X_{\uparrow(n-1)} & \text{if} \quad \overline{X} - X_{n-1}^{bau} - \widetilde{X}_n \leq X_{\uparrow(n-1)} \leq \overline{X} - \widetilde{X}_n - \widetilde{X}_{n-1} \\ \widetilde{X}_{n-1} & \text{if} \quad X_{\uparrow(n-1)} \geq \overline{X} - \widetilde{X}_n - \widetilde{X}_{n-1} \end{cases} \tag{7}$$

The term $X_{\uparrow(n-1)}$ denotes the pollution amount attributable to polluters upstream of $n-1$ and is not to be confused with $X_{-(n-1)}$ which is the pollution amount attributable to all polluters excluding $n-1$. Equation (7) essentially translates equation (6) to the sequential context so that now player $n-1$ takes only upstream pollution ($X_{\uparrow(n-1)}$) as given and their compliance goal explicitly takes the next player's strategy into account.

Player $n-1$ knows that the player n will never choose to pollute below their minimum profitable pollution level ($\widetilde{X}_n$). Therefore, if player $n-1$ wants to achieve a compliance outcome, she must ensure that the water received by n does not exceed $\overline{X} - \widetilde{X}_n$. However, if the water received by $n-1$ is too polluted so that $n-1$ must pollute below her own minimum profitable pollution level to achieve the compliance goal, then she will surely not do so resulting in overall non-compliance. Equation 8 extends the best response function to all players j where j is upstream of n $(j < n)$. For (8) to apply to Player 1, simply set $X_{\uparrow(1)} = 0$.

$$X_j^{BR} = \begin{cases} X_j^{bau} & \text{if} \quad X_{\uparrow(j)} \leq \overline{X} - X_j^{bau} - \sum_{k=j+1}^{n} \widetilde{X}_k \\ \overline{X} - X_{\uparrow(j)} - \sum_{k=j+1}^{n} \widetilde{X}_k & \text{if} \quad \overline{X} - X_j^{bau} - \sum_{k=j+1}^{n} \widetilde{X}_k \leq X_{\uparrow(j)} \leq \overline{X} - \widetilde{X}_j - \sum_{k=j+1}^{n} \widetilde{X}_k \\ \widetilde{X}_j & \text{if} \quad X_{\uparrow(j)} \geq \overline{X} - \widetilde{X}_j - \sum_{k=j+1}^{n} \widetilde{X}_k \end{cases} \tag{8}$$

Now that the best response functions have been derived under both simultaneous and sequential games, we can begin to analyze the welfare under each equilibrium concept.

Welfare in Equilibrium

There is a well known result that the SPNE is a subset of the set of NE's and so when t is set perfectly, there is a unique NE and is thus identical to the SPNE. When t is set too strictly (high), however, the SPNE results in one of the extremes from the set of NE's. Take Figure 4 as an example. Assuming that Player 1 is upstream of 2, the SPNE would produce the point $(\overline{X} - \widetilde{X}_2, \widetilde{X_2})$ as the pollution allocation. This is because Player 1 can exert its first mover advantage over Player 2 by producing more pollution and forcing Player 2 to pick up the slack. Player 2 is happy to do this because of Proposition 0.1. This intuition is captured in Theorem 0.2 and Corollary 0.3.

Theorem 0.2. *If all firms are identical in all but location, then the SPNE resulting from the policy* $(t, \overline{X})$ *where* $t > \lambda^*(\boldsymbol{\theta}, \overline{X})$ *produces a pollution allocation that is non-increasing downstream. That is*

$$X_h^{spne} \geq X_\ell^{spne}$$

where $h < \ell$ *(so that* h *is upstream of* ℓ*).*

See proof on page 24.

Corollary 0.3. *Suppose all firms are homogeneous except location and that* $t > \lambda^*$. *If* $\overline{X} = kX^{bau} + (n-k)\widetilde{X}$ *then the SPNE would produce the following result*

$$(X_1^{spne}, \ldots, X_k^{spne}, \ldots, X_n^{spne}) = (\underbrace{X^{bau}, \ldots, X^{bau}}_{k}, \underbrace{\widetilde{X}, \ldots, \widetilde{X}}_{n-k})$$

Corollary 0.3 simply says that if the ambient standard is can be perfectly allocated so that there are k players choosing BAU levels and the rest choosing the minimum profitable pollution level, then the SPNE would result in such an allocation whereby upstream players enjoy the BAU profits. This formalizes the arguments made in the previous section and shows that SPNE does indeed produce the extreme allocation that is possible when $t > \lambda^*$. Situations where $\overline{X} \neq kX^{bau} + (n-k)\widetilde{X}$ does not change the main results and so we assume that the equality holds for ease of exposition.

The result from Corollary 0.3 and Theorem 0.4 below implies that the SPNE still achieves compliance but at the highest possible cost. This result relies heavily on the homogeneous firm assumption which limits its value somewhat but it does suggest that in situations where the regulator has a strong belief that polluters are homogeneous then it may be worth while to invest the necessary resources to uncover θ for two reasons. First, if the regulator incorrectly sets t it will either not achieve its ambient goals or it will achieve it at greatest cost. Second, since firms are homogeneous, it reduces the cost of learning θ.

Theorem 0.4. *Suppose that firms are homogeneous in all but location and $t > \lambda^*$. Let k be such that*

$$kX^{bau} + (n-k)\widetilde{X} = \overline{X}$$

Then the allocation

$$\vec{X} = (\underbrace{X^{bau}, \ldots, X^{bau}}_{k}, \underbrace{\widetilde{X}, \ldots, \widetilde{X}}_{n-k})$$

produces the lowest welfare possible among all other compliance NE's.

See proof on page 25.

When we start to consider the more realistic scenario where firms are heterogeneous, the welfare consequences of a too strict t value in an SPNE becomes more complicated. The degree to which an SPNE would produce a compliance outcome at higher than least cost depends on the degree to which low θ types are situated upstream of high θ types such that they can free ride. In general, the SPNE would result in producer welfare W^p_{spne} such that

$$W^p_{so} - W^p_{spne} = \sum_{h=k+1}^{n} [\pi_h(X^*_h) - \pi_h(\widetilde{X}_h)] - \sum_{h=1}^{k} [\pi_h(X^{bau}_h) - \pi_h(X^*_h)]$$

where W^p_{so} is the producer welfare under socially optimal pollution allocation. Assume there are high and low theta types so that we get

$$W^p_{so} - W^p_{spne} = (n - k_L)[\pi(X^*_H, \theta_H) - \pi(\widetilde{X}_H, \theta_H)] + k_L[\pi(X^{bau}_L, \theta_L) - \pi(X^*_L, \theta_L)]$$

if all low types are upstream of high types and if vice versa we get

$$W^p_{so} - W^p_{spne} = (n - k_H)[\pi(X^*_L, \theta_L) - \pi(\widetilde{X}_L, \theta_L)] + k_H[\pi(X^{bau}_H, \theta_L) - \pi(X^*_H, \theta_H)]$$

where $k_L > k_H$ since you can pack more of the low types into the free-rider status due to $X^{bau}_L < X^{bau}_H$.

3 Player Example

To try and get some intuition for all of the math, consider a 3 player scenario. Suppose that each firm is the same but location and that their BAU levels of pollution is 50 units each. Further suppose that the regulator sets an ambient standard of 120 units. If the regulator sets the tax rate perfectly, then t is set such that no player would willingly pollute less than 40 units. In other words, if a firm has to pollute less than 40 to avoid the tax penalty, they would find it more profitable to pollute at least 40 units and pay the tax. Clearly a (40, 40, 40) allocation is an NE and it turns out to be unique.

However, if t is set too strictly, then each player would now at a minimum discharge, say, 35 units to avoid the tax penalty. This means that (35, 35, 50) is an NE as well as (35, 36, 49) etc. Turns out that the lowest welfare (highest cost) compliance scenario is any allocation where two players pollute 35 and one player pollutes 50. The SPNE produces a unique equilibrium that gives rise to this exact situation. The first player recognizes that they can pollute at the BAU level 50 and still have the remaining players find it more profitable to abate down to 35 than to pollute more and pay the tax penalty.

Discussion

The results so far suggest that when the regulator can calibrate t perfectly for $\overline{X}$, then there is no difference in the NE and SPNE results. However, if the regulator overshoots λ^* even slightly, then the NE and SPNE diverge. For the case in which polluters are homogeneous in all but location, the SPNE will always produce the worst compliance outcome in terms of welfare. This is because if the t is set too strict (i.e., $t > \lambda^*$), then firms' minimum profitable pollution level ($\widetilde{X}_i$) is lower than the socially optimal individual discharge, X_i. Thus there is a wide range of pollution allocations that can both achieve compliance exactly and is individually rational. But when $t = \lambda^*$, firms' minimum profitable pollution level is exactly equal to the socially optimal individual discharge. This gives no room for alternative allocations that can both achieve the standard exactly and is also individually rational.

This can be potentially problematic for regulators trying to reduce NPS pollution at least cost. Without perfect knowledge about firm types, the NE could achieve the ambient standard at higher than least cost. Furthermore, the tax policy itself may create a sequential game situation where you are guaranteed to have the highest cost scenario when firms are relatively homogeneous in types. One possible solution would be adjust the ambient tax schedule so that there is no tax threshold as in (**??**).

$$T(X) = tX \tag{9}$$

Under this tax schedule, all firms would be facing the marginal incentives intended by the regulator and marginal tax penalties are no longer dependent on other firms' polluting decisions. This would dissolve any strategic behavior and all firms would produce at the point where $\pi'(X_i) = t$. This has the advantage of guaranteeing that the distributional abatement costs are correct.

Some drawbacks of this is that it is not budget balancing, meaning that tax revenues would exceed the damages. Furthermore, tax incidence will need to be carefully weighed with everything else since firms will always face a non-zero tax penalty.

It is also important to note a two important points about the analysis. First, the SPNE concept only makes sense in simple river networks. If there is a fork in the river so that two firms are neither upstream nor downstream from one another, then we no longer have a full information extensive form game. Secondly, the homogeneity assumption is crucial to the result that the SPNE always produces a compliance outcome at the highest cost. When heterogeneity is allowed, the SPNE may no longer be unique and is not guaranteed to produce the worst case scenario. Such a result would depend on the degree to which the lowest cost abaters are situated furthest upstream.

Future Directions and Areas for Feedback

I'd like to say that this is more or less the entire paper and I don't think I will add a numerical or empirical component unless others disagree. However, I do want to try and test empirically whether ordering matters in real life using the data from the Everglades Forever Act which is the only known policy that explicitly has an ambient tax. I have spent a lot of time exploring this policy and getting/cleaning the data and would hate to see that effort go to waste! I'd like to test whether the policy had differential impact on farms' runoff quality based on location. Unfortunately, I'm not sure how to convincingly test the effects of a variable that doesn't change over time in a panel setting.

The data that I have covers all farms that are affected by the tax for all the years in which the policy was active. This panel data has roughly 150 cross sectional units and 24 years of annual data. I have farm level runoff observations, land sizes, a measure of the economic incentive to abate that results from the policy, location of each farm, etc. The policy is such that farms are awarded a tax credit for each unit that the group pollution is below some standard. However, there is a limit to how many tax credits each farm needs so at some point, farms can have more tax credits than they need. The measure of the economic incentive to abate is then characterized by how much credits the farm still needs to earn.

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Appendix: Proofs

Proof of Proposition 0.1. We can rewrite 5 as

$$\max_{X_i^c, X_i^d} \left\{\Pi_i^c, \Pi_i^d\right\} \tag{10}$$

where

$$X_i^c = \arg\max_{X_i} \ \pi_i(X_i) \qquad \text{s.t} \qquad X \leq \overline{X} \tag{10.1}$$

$$\Pi_i^c = \pi_i(X_i^c) \tag{10.2}$$

$$X_i^d = \arg\max_{X_i} \ \pi_i(X_i) - t(X - \overline{X}) \qquad \text{s.t} \qquad X > \overline{X} \tag{10.3}$$

$$\Pi_i^d = \pi_i(X_i^d) - t(X_i^d + X_{-i} - \overline{X}) \tag{10.4}$$

Here, X_{-i} denotes the pollution level of all other players but i. The strategy of player i can be broken down into two types, a comply strategy and a don't comply strategy. The comply strategy and associated payoffs are represented with a superscript c as in (5.1)-(5.2). The don't comply strategy and corresponding payoff is represented with a d as in (5.3)-(5.4).

We want to prove that if $\Pi_i^d \geq \Pi_i^c$, then $X_i^d \geq \widetilde{X}_i$ and if $\Pi_i^d \leq \Pi_i^c$, then $X_i^c \geq \widetilde{X}_i$. We know that $X_i^d \geq \widetilde{X}_i$ regardless. This follows immediately from Proposition 0.1 and (10.3). If the constraint from (10.3) is not binding then $X_i^d = \widetilde{X}_i$. If it is binding then $X_i^d > \widetilde{X}_i$. Thus we've proved the first part.

For the second part, recognize that if $\widetilde{X}_i + X_{-i} \leq \overline{X}$ then $X_i^c \geq \widetilde{X}_i$ by definition. It can then be shown that $\Pi_i^c \geq \Pi_i^d$ if and only if $\widetilde{X}_i + X_{-i} \leq \overline{X}$. I prove this below.

Suppose that $\Pi_i^c \geq \Pi_i^d$.

$$\iff \pi(X_i^c) \geq \pi(X_i^d) - t(X - \overline{X})$$

$$\iff t(X - \overline{X}) \geq \pi(X_i^d) - \pi(X_i^c)$$

$$\iff t(X_i^d - X_i^c) \geq \pi(X_i^d) - \pi(X_i^c) \qquad \text{(add/subtract by } t(X_i^c) \text{ to LHS)}$$

$$\iff t \geq \frac{\pi(X_i^d) - \pi(X_i^c)}{X_i^d - X_i^c}$$

Note that there are only two possibilities, either the "don't comply" (DC) constraint binds $(\widetilde{X}_i + X_{-i} \leq \overline{X})$ or it doesn't $(\widetilde{X}_i + X_{-i} > \overline{X})$. When the DC constraint binds, then we have $\widetilde{X}_i \leq X_i^c < X_i^d$. When it fails to bind, we have $X_i^c < X_i^d = \widetilde{X}_i$.

Since we know that $t = \pi'(\widetilde{X}_i)$, then if $t \geq \dfrac{\pi(X_i^d) - \pi(X_i^c)}{X_i^d - X_i^c}$ holds, it must be the case that the DC constraint binds since both X_i^c and X_i^d are to the right of $\widetilde{X}_i$. When the DC constraint fails to bind, (i.e., $X_i^d = \widetilde{X}_i$ and $X_i^c < \widetilde{X}_i$), then the slope condition will fail to hold also. Thus

$$\Pi_i^c \geq \Pi_i^d \iff \widetilde{X}_i + X_{-i} \leq \overline{X} \qquad \text{(DC constraint binds)}$$

$\square$

Proof of Theorem 0.2. The proof follows directly from Equation (8). For example, take the first line from the piecewise function and compare this for two different players, h and ℓ

where h is upstream from ℓ. Player h will pollute X^{bau} if $X_{\uparrow(h)} \leq \overline{X} - X_h^{bau} - (n-h)\widetilde{X}$ and Player ℓ will also pollute X^{bau} if $X_{\uparrow(\ell)} \leq \overline{X} - X_\ell^{bau} - (n-\ell)\widetilde{X}$. Since we have

$$X_{\uparrow(\ell)} > X_{\uparrow(h)}$$

and

$$\overline{X} - X_\ell^{bau} - (n-\ell)\widetilde{X} > \overline{X} - X_h^{bau} - (n-h)\widetilde{X}$$

it is hard to tell which player is more likely to play their BAU levels at the moment. However, we can establish that

$$X_{\uparrow(\ell)} - X_{\uparrow(h)} > (\ell - h)\widetilde{X}$$

since players in between h and ℓ would, at a minimum, produce $\widetilde{X}$. This then allows us to claim that the condition for h to play their BAU level is more likely to hold than the condition for ℓ to play their BAU level. A similar process can be done for the remaining pieces from (8) to fully establish the proof. □

Proof of Theorem 0.4. The welfare from Proposition 0.4 is given by

$$W_0 = k\pi(X^{bau}) - (n-k)\pi(\widetilde{X}) - D(\overline{X})$$

but since all NE's result in compliance, the damage function will be same when comparing across different NE's and there is no tax incurred. Thus, the only relevant comparison is done on producer welfare, W_0^p given by

$$W_0^p = k\pi(X^{bau}) - (n-k)\pi(\widetilde{X})$$

The only possible reallocation will be one in which a free rider will pollute ε less while a contributor will pollute ε more. Such a reallocation produces welfare W_1^p where

$$W_1^p = (k-1)\pi(X^{bau}) + (n-k-1)\pi(\widetilde{X}) + \pi(X^{bau} - \varepsilon) + \pi(\widetilde{X} + \varepsilon)$$

Then evaluating $W_0^p - W_1^p$

$$\begin{aligned} W_0^p - W_1^p &= \pi(X^{bau}) - \pi(X^{bau} - \varepsilon) + \pi(\widetilde{X}) - \pi(\widetilde{X} + \varepsilon) \\ &= \pi(X^{bau}) - \pi(X^{bau} - \varepsilon) - \left[\pi(\widetilde{X} + \varepsilon) - \pi(\widetilde{X})\right] \\ &\leq 0 \qquad \text{(since } \pi'(x) \text{ is decreasing in } x \text{ for } x \leq X^{bau}\text{)} \end{aligned}$$

$\square$

	Loads-CV-No-Trend	Loads-BV-No-Trend	Loads-CV-Lin-Trend	Loads-BV-Lin-Trend	Loads-CV-Quad-Trend	Loads-BV-Quad-Trend	TP-CV-No-Trend	TP-BV-No-Trend	TP-CV-Lin-Trend	TP-BV-Lin-Trend	TP-CV-Quad-Trend	TP-BV-Quad-Trend
Credits Still Needed (not mult by L)	-0.00566		-0.00255		-0.00705*		-0.235		0.294		0.241	
	(0.00274)		(0.00154)		(0.00206)		(0.210)		(0.214)		(0.0949)	
interact2	0.000000207		0.000000227		0.000000245		-0.00000458	-0.00000669	-0.00000731		-0.00000711	
	(0.000000120)		(0.000000127)		(0.000000120)		(0.0000107)	(0.0000155)	(0.0000144)		(0.0000135)	
v_acres_total	0.0000490	0.0000406	-0.0000378	-0.0000631	-0.0000134	-0.0000192	0.00221	0.00194	-0.00226	-0.00243	-0.00195	-0.00135
	(0.0000411)	(0.0000387)	(0.0000663)	(0.0000625)	(0.0000702)	(0.0000640)	(0.00175)	(0.00152)	(0.00370)	(0.00287)	(0.00245)	(0.00191)
Basin Acreage	0.0000251	0.0000232	0.0000411	0.0000421	0.0000340	0.0000323	-0.00192	-0.00193	-0.00251	-0.00226	-0.00260	-0.00249
	(0.0000128)	(0.0000125)	(0.0000170)	(0.0000177)	(0.0000161)	(0.0000172)	(0.00236)	(0.00272)	(0.00210)	(0.00211)	(0.00246)	(0.00231)
treat		0.603		0.389		0.973		18.48		-18.30		-4.912
		(0.319)		(0.205)		(0.391)		(12.27)		(33.60)		(20.63)
interact1		-0.0000186		-0.0000222		-0.0000249				0.000283		0.000235
		(0.0000139)		(0.0000150)		(0.0000147)				(0.00186)		(0.00178)
trend			-0.0217**	-0.0314**	-0.171**	-0.189*			2.396*	2.169	0.550	-1.853
			(0.00408)	(0.00575)	(0.0423)	(0.0641)			(0.636)	(0.918)	(7.948)	(3.380)
trend_sq					0.00497*	0.00534					0.0615	0.134
					(0.00144)	(0.00208)					(0.276)	(0.131)
Constant	1.007***	0.791**	1.171***	1.390***	2.170***	1.904**	25.61	6.672	-15.45	0.396	-3.195	14.92
	(0.00350)	(0.112)	(0.0836)	(0.168)	(0.238)	(0.303)	(12.08)	(21.26)	(8.507)	(12.03)	(56.13)	(13.56)
N	3819	3819	3833	3833	3833	3833	3547	3547	3560	3560	3560	3560
Rsqr	0.395	0.393	0.347	0.342	0.354	0.354	0.385	0.385	0.363	0.363	0.363	0.363
A-Rsqr	0.347	0.345	0.314	0.308	0.321	0.321	0.334	0.334	0.329	0.329	0.329	0.329
Fstat	.	.	.	.	.	.	.	.	.	.	.	.

Standard errors in parentheses

Standard errors are clustered at the sub-basin and break point levels

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$