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What is the Right Ambient Water Quality Tax?

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Abstract

This paper presents an extension and empirical application of Segerson's nonpoint pollution control mechanism. Segerson's incentive is designed to eliminate free riding by requiring each polluter to pay the full marginal cost of pollution for ambient water quality worse than a target, or to be subsidized for water quality better than that target. The magnitude of the incentive necessary to achieve a specified target depends on the assumed behavior of farmers: if they collude, a lower incentive level will achieve the same ambient water quality as a higher incentive if farmers act independently. Alternatively, an incentive level designed under the assumption that farmers will act independently will lead to greater abatement and subsidy payments to farmers if they collude. Thus, regulators need to consider how farmers will respond to each other when they calculate an incentive level. An empirical application is made to lettuce production in California's Salinas Valley.

1. INTRODUCTION

Segerson [10] in 1988 presented a theoretical paper on "Uncertainty and Incentives for Nonpoint Pollution Control," which developed a general incentive mechanism to control nonpoint source pollution based on observed ambient levels of pollution. The incentive scheme rewards polluters for environmental quality above a given standard or penalizes for substandard quality. This mechanism is developed on the premise that "standard pollution control devices such as direct regulation or the use of emission taxes are inappropriate for nonpoint pollution problems characterized by physical uncertainty and monitoring difficulties." The paper considers single and multiple polluters, where the incentive ensures socially optimal abatement levels by the polluters. For multiple polluters (generally the case), this mechanism is designed to eliminate free riding.

The difficulties arising from effectively regulating nonpoint source pollution emanate from the inability to observe pollution from individual sources. Observed ambient pollution depends on climate, topography, and the behavior of polluting entities, all of which vary across sources. As a result, the actions of individual polluters cannot be inferred from observing ambient levels. Segerson represents the range of possible ambient pollution levels by a probability density function conditional on the abatement behavior of individual polluters. Increasing the probability that ambient pollution falls below a specified level is the specified objective.

The socially desirable level of abatement by each contributor is achieved with an incentive designed such that every polluter is jointly liable for the ambient levels of pollution. Since each polluter's liability depends on total ambient levels, this mechanism eliminates free riding. Considering the geographic size of an agency-controlled region, the socially desirable level of pollution reduction, and the number of polluters, incentives designed in this fashion can create large financial impacts. As a consequence, individual polluters have incentives to collude to achieve potentially greater incentive rewards by coordinating abatement activities.

This paper presents an extension and empirical application of Segerson's nonpoint pollution control mechanism by examining the effects of the ambient water quality tax when heterogeneous polluters can pursue either Cournot or cartel strategies. The empirical application is nitrate leaching to groundwater from crisphead lettuce production in California's Salinas Valley.

This region of California is one of the largest vegetable producing areas in the nation; at the same time, decades of agriculture have decreased the groundwater table and flow, resulting in saltwater intrusion and nitrate contamination. Nearly all of the resident drinking water comes from public wells, several of which have been closed due to high nitrate levels. The State Water Resources Control Board has begun the process of evaluating the damage of groundwater from agriculture and how best to control the quality of the region's groundwater. The Segerson mechanism provides an innovative approach to controlling nonpoint source pollution in the presence of uncertainty and monitoring difficulties, yet specific attention is warranted in designing the correct incentive when there is the possibility of farmers colluding.

2. THE MODEL

The notation and presentation here is revised from that in Segerson's paper, in order to make it closer to the empirical analysis to follow. Additionally, for emphasis on the market structure issues, uncertainty is eliminated from the model. Let x be a measure of the ambient water pollutant of concern, with \bar{x} the target level of that pollutant. Each farm, indexed by $i = 1, \dots, N$, produces a contribution g_i to that pollution level, where g_i is defined so that $\sum_{i=1}^N g_i = x$ (that is, g_i is the effect on ambient water quality of discharge from farm i). Each farm produces crop y_i with price p and cost function $C_i(y_i, g_i)$ ($\partial C_i / \partial y_i > 0$, $\partial^2 C_i / \partial y_i^2 \geq 0$, $\partial C_i / \partial g_i < 0$, $\partial^2 C_i / \partial g_i^2 \geq 0$).

One version of Segerson's proposed instrument, if marginal benefits are assumed linear, is $T(x) = t(x - \bar{x})$, where t is set to equal the full marginal cost of pollution. All firms will be taxed the same amount if the ambient pollution level exceeds the target, and they will all be subsidized the same amount if water quality is better than the target. Since the costs of additional ambient pollution are borne by each polluter, marginal incentives are not distorted and the free rider problem is eliminated. An individual firm's profit expression thus becomes

$$(1) \quad \pi_i = py_i - C_i(y_i, g_i) - t\left(\sum_{i=1}^N g_i - \bar{x}\right), \text{ with first-order conditions}$$

$$p - \partial C_i / \partial y_i = 0$$

$$-\partial C_i / \partial g_i - t = 0.$$

Each firm thus faces the same marginal incentive t to clean up its pollution. Each farm will then choose a level of pollution $g_i(t, p)$ ($dg_i/dt < 0$ from comparative statics results), with resulting ambient water quality $x = \sum_{i=1}^N g_i(t)$; with sufficient information, a regulatory agency can set t and \bar{x} so that farms are neither taxed nor subsidized. (Alternatively, the agency can experiment with t to achieve the desired water quality level with no payments.)

Because ambient water quality depends on the joint actions of the N agents, the pollutant load imposed by each farmer affects the tax that other farmers will pay. Thus, the above conditions apply if farmers act independently on each other. Alternatively, farmers can collude. If the farmers coordinate their activities, they will maximize joint profits, with the objective function

$$(2) \quad \sum_{i=1}^N \pi_i = \sum_{i=1}^N [py_i - C_i(y_i, g_i)] - N \cdot t \left(\sum_{i=1}^N g_i - \bar{x} \right), \text{ with first-order conditions}$$

$$p - \partial C_i / \partial y_i = 0 \text{ for } i = 1, \dots, I$$

$$-\partial C_i / \partial g_i - N \cdot t = 0 \text{ for } i = 1, \dots, N.$$

Because the farmers are colluding, they recognize that, every time one farm increases its pollutant contribution, that farm increases the ambient water quality tax not only on itself, but also on all the other farmers. As a result, the farms act as though they face a higher tax, which induces greater cleanup for a specified tax. (Alternatively, a tax set at t/N when farmers are colluding will achieve the same result as a tax set at t when farmers are not colluding.) If a regulator proposes a tax meant to induce neither tax nor subsidy payments when farmers act independently, collusion among farmers will lead to even more pollution reduction and thus require a subsidy payment to them.

Unlike the classic model of firms colluding on output levels, combining all farms under one owner will not achieve the collusion result. The benefit of colluding comes from reducing aggregate tax payments $N \cdot t$; if N becomes one, there is no difference between the cartel and Cournot scenarios. Thus, the benefits of cartel increase with the number of firms, at the same time that enforcing the cartel becomes more difficult.

As with traditional cartels, farmers in this model have an incentive to cheat on the cartel. From the above model, under the cartel each farmer will pollute $g_i^*(N \cdot t, p)$. Farmer 1 will then face the profit function

$$(3) \quad \pi_i = py_1 - C_1(y_1, g_1) - t(g_1 + \sum_{i=2}^I g_i^*(N \cdot t, p) - \bar{x}), \text{ with first-order conditions}$$

$$p - \partial C_1 / \partial y_1 = 0$$

$$-\partial C_1 / \partial g_1 - t = 0.$$

This farmer, by ignoring the effects of her own behavior on the tax faced by other farmers, will want to base her pollution on the actual tax. Since $t < N \cdot t$, this lower actual tax will result in higher pollution than under the perceived higher tax of the cartel. There is thus a strong incentive for farmers to cheat on the cartel, unless farmers can easily enforce collusion.

Segerson's proposed ambient water quality tax has many desirable features from a policy perspective: it requires only one measurement (ambient water quality), which can easily be conducted, and it can achieve an efficient outcome without identifying individual farm's pollution levels. Among its disadvantages, though, is the ambiguity in the effects of a tax/subsidy level, due to uncertainty in farmers' ability and desire to collude. If a regulator premises the level of t on the assumption that farmers will behave Cournot, but farmers collude, the agency could face potentially large subsidy payments; alternatively, if the regulator assumes that farmers will collude, but in fact the cartel breaks up, water quality will suffer. This paper will develop empirical calculations of the magnitudes of these effects for Salinas Valley farmers.

3. THE SETTING

The Salinas Valley in Monterey County, California is one of the largest producers of high-valued vegetable crops in the country. Lettuce is one of the primary vegetable crops with most of the region's acreage devoted to this commodity. While lettuce in Monterey County contributes nearly \$500 million annually to gross farm revenue[6], it contributes as well to substantial levels of nitrates in the groundwater [1, 2, 5, 8].

Lettuce in this region is generally double-cropped with a planting in the spring and another during the summer. Weather conditions are dry and warm during the planting months, with rain occurring mainly in the winter. It takes approximately three months from planting until harvest.

The crop is initially irrigated by sprinkler until a root system is established, and then furrows are used to irrigate the lettuce crop. Nitrogen fertilizer is applied by injection along the furrows. The source of water for irrigation is groundwater pumped from private farm wells.

This paper examines lettuce grown on three of the major soil types in this region -- Mocho silt loam, Pacheco silty clay loam, and Chualar loam. Each of these soils have differing characteristics, contributing to differences in crop production, water and nitrogen requirements for crop growth, and nitrate leaching. Mocho and Pacheco are similar, though Mocho is slightly more sandy and thus leaches inputs more readily past the crop root zone. Chualar is highly sandy with very little clay. More inputs are required, and nitrate leaching occurs more rapidly on this soil type.

The abatement strategy taken by farmers in this study is reduced application of irrigation water and nitrogen fertilizer. It is assumed that farmers know the estimated effects that water and nitrogen fertilizer have on crop production and nitrate leaching, although the latter may be more difficult for farmers to observe directly. Today, farmers in this region are beginning to use modern testing methods to measure soil moisture and soil nitrogen content as means to determine the crop's water and fertilizer needs. From this information, farmers can estimate the residual nitrogen and water in the field leading to potential nitrate leaching beyond the crop root zone.

Some of the farmers in this area plant winter rye grass as a cover crop to conserve nutrients in the soil and protect nitrate residuals from leaching during winter rain. Crop production and input use are not affected by cover crop planting because the grass is incorporated into the soil at least one month prior to planting; nutrients remaining in the soil from the cover crop do not influence farmers' decisions on irrigation or fertilizer application. In this study, a fixed proportion of the farmers is presumed to plant cover crops as a pollution reducing practice.

4. THE PROGRAMMING MODEL

In this paper, ambient nitrate leached is assumed to be an accumulation of nitrate leached from each of the farm types studied. Since it may take up to 20 years for nitrate from the surface soil layers to leach into the groundwater, the incentive in this model can be thought as the future benefit of an added unit of abatement.

Nonlinear programming is employed to determine optimal abatement strategies by polluters. Segerson's model assumes each polluter is a Cournot firm and that a Cournot-Nash equilibrium induces polluters to choose the socially optimal abatement strategy. From equation (1), farmer i 's problem is to choose water and nitrogen inputs, which directly determine crop output and nitrate leaching, to maximize

$$(4) \quad \pi_i = py_i(w_i, n_i, z) - p^w w_i - p^n n_i - t[g_i(w_i, n_i, z) + \sum_{j \neq i}^N g_j - \bar{x}],$$

where w_i and n_i are water and nitrogen (with p^w and p^n their respective prices), and z is a vector of exogenously determined variables, the components of which are described in the data section. Here the cost of crop production and abatement is simply the cost of water and nitrogen use, which implies that the problem is one of quasi-rents maximization. The incentive is designed so that it is a tax (subsidy) when the aggregate pollution is greater (less) than the ambient pollution target. A cobweb approach is used to solve the Cournot-Nash equilibrium: an iterative loop solves equation (4) for each polluter given the abatement strategy of other polluters. Initially, the abatement level of other polluters is chosen arbitrarily, but each farmer's pollution level (through the choice of water and nitrogen) converge to the Cournot-Nash equilibrium when the optimal abatement level and the value of the objective function do not change.

If farmers behave as a cartel, their individual abatement levels are chosen jointly and they face an aggregated tax incentive. Equation (4) can be slightly modified to exhibit this behavior:

$$(5) \quad \sum_{i=1}^N \pi_i = \sum_{i=1}^N [py_i(w_i, n_i, z) - p^w w_i - p^n n_i] - N \cdot t[\sum_{i=1}^N g_i(w_i, n_i, z) - \bar{x}].$$

If an agency determines taxes assuming Cournot behavior but the polluters act as a cartel, then the incentive may be large enough to induce over-abatement, resulting in subsidy payments to the cartel.

In this paper, results from the Cournot and cartel models on estimated farm quasi-rents and pollution levels are compared over a range of ambient pollution targets. Different targets can have varying effects on quasi-rents and pollution levels between farms. In this study, the incentive t chosen in modeling various ambient pollution targets under the Cournot assumption is set to achieve a specified level of pollution with no tax or subsidy actually paid. In other words, this

“revenue-neutral” incentive induces each farmer, acting independently, to choose the level of abatement which results in ambient pollution being exactly the level of the target. (This scheme does not necessarily imply that the abatement level chosen by each farmer is socially optimal, since the level of the tax may not represent the social marginal benefit of abatement. The model developed in this way achieves the level of ambient pollution reduction at a minimum cost rather than at a social benefit maximum.) The programming model in (4) can be modified so that each farmer chooses water and nitrogen inputs to maximize

$$(6) \quad \pi_i = py_i(w_i, n_i, z) - p^w w_i - p^n n_i$$

$$\text{subject to } g_i(w_i, n_i, z) + \sum_{j \neq i}^N g_j = \bar{x},$$

where the shadow value on the constraint is equivalent to the tax incentive t . The program used to simulate cartel behavior using Cournot-based tax incentives is equation (5), with the tax/subsidy incentive coming from the shadow value in (6). Since, under this scenario, the shadow value is N times larger than the incentive needed to induce revenue-neutral ambient pollution levels for the cartel, farm collusion will induce over-abatement and result in ambient pollution levels less than the agency-desired target.

5. DATA

Field data on nitrate leaching in response to irrigation water and nitrogen fertilizer applications for crop production rarely exist, making empirical studies of nonpoint source pollution difficult to conduct. To overcome this difficulty, an agronomic model which simulates nitrate leaching from crop production based on available field data is employed. A description of the agronomic model and field data used in calibrating the agronomic model can be found in Jackson, Stivers, Warden, and Tanji [5] and House[4].

The variables explaining the crop and nitrate production functions for each of the soil types are irrigation and nitrogen fertilizer applications, initial soil nitrate concentration (the nitrate residue in the soil from the previous crop), and annual weather patterns (average seasonal temperatures and rainfall). A generalized polynomial model (Lau [6]) is used because it fit well for predicting nitrate and crop production and outperformed other functional forms examined. Crop and nitrate production function estimations along with the observations can be obtained

from the authors. Ambient pollution levels x are assumed to be affected by the sum of individual soil type leachate, g_i : that is, a reduction in x will be achieved through reductions in $\sum_{i=1}^3 g_i$.

Price data consist of water and nitrogen prices and lettuce prices. The price of water is \$0.25 per millimeter-hectare, based on the electricity costs for pumping groundwater from the average well depth in the Salinas Valley. Average nitrogen fertilizer costs are \$0.37 per kilogram [11]. Lettuce prices net of harvesting cost are \$1510 per metric ton (dry weight) [8]. The average cost to farmers in planting and managing the winter rye cover crop is estimated at \$262 per hectare. Nitrate leaching without a cover crop is estimated to be 260, 172, and 449 kilograms per hectare for Mocho, Pacheco, and Chualar soils, respectively. Chualar leaches more nitrates because it is a more sandy soil and the applied water and nitrogen fertilizer flow rapidly below the crop's root zone. Mocho and Pacheco soils are similar, though Mocho is more porous than Pacheco. Previous studies [7, 3] have suggested that reducing water application is more effective in reducing nitrate leaching than reducing fertilizer applications.

The distribution of soil types between farms is based on examining soil map studies in the Salinas Valley [12]. It is assumed, based on these studies, that 40% of the land planted to lettuce is grown on Mocho silt loam, 40% on Pacheco silty clay loam, and 20% on Chualar loam. Winter cover crops are estimated to be planted on 50% of each of those soil types, based on current farmer behavior, although treating cover crops endogenously as an additional choice abatement variable in the programming model could be considered. For modeling purposes, each soil type-cover crop combination is considered a separate farm, resulting in six farms.

6. RESULTS

Pollution reduction targets ranging from 0% to 50% reduction at 5% increments are compared. For the same target abatement levels for a given farm, the Cournot and cartel cases result in the same levels of input use, and therefore the same nitrate leaching and quasi-rent, although, as shown in the theory, the tax necessary to achieve these levels differs by a factor of N between the two scenarios. This implies that, given their respective "correct" tax levels, the same optimal abatement levels occur for both the Cournot and cartel-behaving farmers (ignoring for now the possibility of farmers ceasing operation). The resulting leaching levels and quasi-rents

are presented in Tables I and II. The associated (revenue-neutral) taxes that induce farmers in aggregate to pollute the targeted level are displayed in Figure I. These taxes are the "minimum cost" incentives to induce the desired response by farmers. Taxes range from \$0 to \$4 per kilogram-hectare of nitrate abated assuming cartel-behaving farmers, and from \$0 to \$25 for the Cournot case.

Figure II presents the effects of these taxes/subsidies under two different behavioral scenarios: first, that a regulator assumes that farmers will behave Cournot and that they do (Cournot-Cournot); secondly, that the regulator assumes that farmers will behave Cournot but instead they collude (Cournot-cartel). Because the Cournot-Cournot scenario is designed to be revenue-neutral (that is, the regulator chooses the tax/subsidy as well as the ambient water quality target so that farmers exactly achieve the target and thus induce no transfers), quasi-rents are reduced due only to changed input levels and the resulting changes in output and profits. As the figure shows, a 50 percent reduction in runoff can be achieved with less than 10 percent reduction in aggregate quasi-rents.

On the other hand, as shown in Figure II, if the regulator assumes that farmers will behave Cournot, but in fact they collude, the farmers will increase their income quite substantially. The tax, which they treat under collusion as being six times higher than under Cournot, induces much more cleanup than the regulator expects, leading to large subsidy payments. Indeed, it becomes desirable for Chualar soils (which leach heavily) to exit production for nitrate reductions of 15-20 percent, and for Mocho (which leach more than Pacheco but less than Chualar soils) soils to cease producing for nitrate reductions of 35-40 percent (see Table IV). (Subsidy payments are shown explicitly in Table IV and are proportionally included in individual farm quasi-rents.) Having these farmers leave lettuce production provides more leaching potential and therefore greater production potential to those farms with "better" soil type. In reality, the farmers leaving would either idle their land with the benefit of sharing the subsidy payment or rotate into planting crops which use less water and nitrogen inputs.

Despite this average increase in quasi-rents under the Cournot-Cartel scenario, the distribution of those quasi-rents is quite uneven. Chualar soils, and Mocho soils with no cover

crop, have their quasi-rents reduced under this scenario, while quasi-rents for Pacheco soils generally increase, especially with cover crops (compare Tables II and IV). Success of collusion, then, requires a mechanism for side payments among farmers.

This analysis has displayed the potential effects that collusion would have from an agency misspecifying the behavior of farmers and setting incentive taxes too high. If farmers face Cournot-based tax/subsidy and target and do not collude, they will face reductions in quasi-rents due to changes in input use (and thus output and profits), but these reductions are not enormous: a 50 percent reduction in nitrate leaching can be achieved with roughly a 10 percent reduction in quasi-rents. Under the Cournot-cartel scenario, ambient water quality improves much more dramatically, resulting in unexpected and high subsidy payments to farmers. Indeed, in the aggregate, farmers benefit from greater regulation due to higher subsidy payments. Because the distribution of quasi-rents under the Cournot-cartel scenario are very uneven, farmers have a strong incentive to cheat on the cartel, unless side payments can be assured and enforcement monitored. If the cartel falls apart, the Cournot-Cournot scenario is likely to result.

7. SUMMARY AND CONCLUSIONS

The Segerson incentive instrument for controlling nonpoint source pollution offers a promising direction in the presence of physical uncertainty and monitoring difficulties. The instrument is designed to increase the probability that ambient pollution levels will fall below some specified tolerance level. An incentive (either positive or negative) based on ambient pollution requires every polluter to pay the total marginal benefit of ambient abatement rather than just its share. Regulation on an ambient level is required because, in this setting, pollution from individual heterogeneous sources can be neither observed nor inferred from the ambient level. Free riding is eliminated in this approach since the costs of additional pollution are borne by each polluter in a way that marginal incentives to abatement are not distorted.

Segerson's paper includes the assumption that each farmer assumes that other farmers will hold their level of pollution constant (the Cournot assumption). This paper extends Segerson's incentive instrument to investigate the effects of farmers colluding as an alternative behavioral assumption. Collusion leads to greater abatement for a given level of the tax, since the benefits of

reducing effluent extend to multiple farmers. At the same time, as with cartels in other situations, farmers have an incentive to cheat on the cartel. While joint profits will be higher if farmers collude than if they act independently, each individual farmer will be better off by acting independently.

The effects of these alternative behavioral assumptions are examined in a case study of lettuce producers in California's Salinas Valley, where nitrate leaching poses a significant nonpoint pollution problem. Not only are there pending regulatory threats from the State to control water pollution in this region, but the social costs are directly apparent by the recent closure of several municipal groundwater wells.

The results indicate that Cournot-based tax incentives will induce farmers, in collusion, to achieve ambient pollution levels lower than the agency-specified pollution target, thereby providing subsidies to these farmers. This potential behavior illustrates a concern that policy makers need to consider when setting taxes to improve ambient water quality. As the pollution reduction target becomes more stringent, the Cournot-based tax becomes larger, creating a greater inducement for farmers to collude, potentially leading to over-abatement and unexpected subsidy payments by the regulator. Even accounting for the transactions costs to farmers of colluding (not explicitly addressed in the model), the benefits of collusion compared with costs are likely to increase with the pollution reduction target. Therefore, an agency implementing this mechanism to control nonpoint pollution needs to recognize that farmer behavior can have a significant effect both on ambient water quality and on the budget for the agency.

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