NONPOINT SOURCE WATER POLLUTION

CONTROL: INCENTIVES THEORY APPROACH

DISSERTATION

Presented in Partial Fulfillment of the Requirements for
the Degree Doctor of Philosophy in the Graduate
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By

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ABSTRACT

The purpose of this study was to design a regulatory policy to solve a nonpoint source (NPS) water pollution problem.

Cost-sharing programs of various kinds have dominated NPS policy since the 1980’s. However, such programs are neither efficient nor effective. Economists agree that, in principle, performance-based approaches are preferred to design-based, because they allow firms to choose least-cost abatement practices. However, nonpoint sources are seldom included in performance-based programs since it is very costly to monitor the performance of individual NPS polluters.

The NPS pollution problem can be modeled as a generalized principal-agents problem. That is, the principal has to regulate agents while he cannot observe either the types and or the effort level of the agents; only total level of ambient pollution is verifiable. However this kind of problem is very complicated and a general solution has yet to be derived. Simplified models (with either only adverse selection, or hidden
action) have been analyzed and first best solutions derived. Nevertheless, these solutions are incomplete, since they fail to solve simultaneously the adverse selection and moral hazard problems.

I show that under assumptions consistent with the NPS pollution situation it is possible to decompose the generalized principal-agent problem into two univariate variational problems in the multi-agents case, and to design a two-step contract that solves both the adverse selection and the hidden action problems.

I offer a policy-maker’s algorithm that can be used to design a regulatory policy to control NPS pollution. Three steps of a transaction – property rights/initial endowment assignment, price and quantity determination, and money/product exchange – are considered sequentially; an optimal regulatory intervention is chosen for each step; and then the whole policy is evaluated for consistency and for as-yet-unexamined effects on related markets. Inconsistencies and undesired general equilibrium effects are resolved by modifying the intervention at the appropriate step and re-iterating through the policy algorithm.

This research has resulted in contributions in three areas of
economic theory: policy design, mechanism design (the generalized principal agent problem), and environmental economics (the nonpoint source water pollution problem).
DEDICATION

To My Kids: Ivan and Jenny Pushkarsky
And Parents: Nina and Nikolay Buchnev
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CHAPTER 1

INTRODUCTION

Nonpoint Source Water Pollution Problem

Among the most important issues human society currently faces is a clean environment. For years human society has been enjoying the benefits of technological progress such as machinery, chemicals, etc. However, the cost of this progress is polluted air, water, and land.

In the United States, public concern over the degradation of water resources has led to a number of federal, state, and local policies for protecting and improving water quality. The most important is the Clean Water Act of 1972. Since the implementation of that act, water quality has been improved largely through reductions in toxic and organic chemical loadings from point sources.
Although the pollution has been largely controlled for point source pollution (PS), the nonpoint source pollution (NPS) problem remains and its importance increases as effectiveness of point source water pollution regulation improves. In fact it has been estimated that up to 70 % of current water pollution comes from nonpoint sources (Clean Water Action Plan, 1998).

To commemorate the 25th anniversary of the Clean Water Act, the White House asked federal agencies to develop and implement a comprehensive plan that would further reduce pollution. This resulted in the Clean Water Action Plan in February 1998. This plan targeted both point source and nonpoint source pollution (See description of point source pollution and nonpoint source pollution below). The key actions described in this Action Plan focus on achieving cleaner water by strengthening public health protections, targeting watershed protection efforts at high priority areas, providing communities with new resources to control polluted runoff and enhancing natural resource stewardship. Controlling polluted runoff appears in 111 key actions specified in the Action Plan.
The motivation for this research was the combination of the great need for effective regulation of nonpoint water pollution, including that from farms runoff, and the insufficiency of methods offered to deal with such problems in the current economic literature.

**Point vs. Nonpoint pollution**

Water pollution may be categorized into two categories: point source and nonpoint source pollution.

Point source pollution enters water directly through a pipe, ditch, etc. Nonpoint source pollution enters water diffusely in three different ways:

1. **runoff**, in which pollutants are transported over the soil surface by rainwater, melting snow, or irrigation water;

2. **run-in**, in which pollutants are transported directly to ground water through sinkholes and porous or poorly constructed wells;

3. **leaching**, in which pollutants are transported through the soil by rain, melting snow, or irrigation water.
Therefore, while it is relatively easy to determine who the polluter is and how much he has polluted in the case of point source pollution, in the non-point case it is usually difficult and costly.

Obviously this difference between point and non-point pollutions affects the applicability of available regulation instruments and policies toward the polluters. Instruments that readily can be applied to point source pollution (standards, tax, pollution permits) present major difficulties in the nonpoint source pollution case.

Various policies have been implemented, but economists have been quite critical of them. The major critiques are the very high cost of environmental programs combined with the lack of efficiency of those programs, and the lack of evidence of measurable reduction of nonpoint source pollution as a result of implemented policies. Economists have also attempted to design improved policies and regulatory instruments, but these have limitations of various kinds. Some of them are inherently inefficient, and some are not applicable since they do not solve the asymmetric information problem.
Therefore the NPS regulation problem remains. Chapter 2 provides a review of current pollution control policies and literature on the topic.

Purpose of the Study

The purpose of this study is to develop a policy to control Nonpoint Source Water Pollution from farms’ runoff that is better than policies currently implemented in practice and better than policies proposed in the economic literature.

In particular, the intent of the study is to design a mechanism that can deal with both kinds of asymmetric information typical for the NPS problem - adverse selection and moral hazard, and has various desirable properties – uses subsidies, which is consistent with traditional approach of policies applied to farmers; efficient, i.e. marginal cost of production an extra unit of abatement is equal to marginal benefit of producing that extra unit for both individual farmers and society; budget balancing, i.e. total money transfer from the regulator is greater or equal to the sum of money
transfers to farmers; in dominant strategies, which insures that the mechanism can work in both certainty and uncertainty cases.

This work is, then, a contribution to the NPS policy discussion and to the mechanism design literature.

The Approach in the Study

Although it is expensive (often prohibitively so) to observe individual farmers’ emissions, it is possible to measure the total increment in ambient pollution from a watershed. It may be safely assumed that point and nonpoint sources that work in the watershed produce together a total level of pollution that can be measured. Effluents produced by point sources can be measured. Therefore, the Regulator can determine the total level of ambient pollution abatement that can be attributed collectively to the farmers in the watershed (this may require adjustments for non-farm NPS), and seek to design a regulatory policy that rewards the farmers collectively for their contribution to abatement.
To design an effective policy that can be applied to a watershed in this study it is proposed to consider the nonpoint pollution problem as a combination of four sub problems. In particular, the four following questions should be answered:

1. Who should pay for the reduction of pollution from a watershed?

   This question is related to the property right or initial endowment assignment and is resolved through the choice between taxes and subsidies. When the Regulator chooses to tax polluters, he is operating on an implicit societal right of receptors to clean water. When he chooses to subsidize polluters for reduction of pollution, he implicitly accepts the right of polluters to pollute at the baseline level.

2. What is the optimal amount of abatement that should be produced in the watershed and what is the optimal price for the unit of this abatement?

   The optimal amount and optimal price are those that are efficient (*marginal benefit from production of an extra unit of*
the abatement is equal to marginal cost of production of this extra unit) both for the society and for individual polluters.

3. How should the optimal level of abatement be allocated among farmers in the watershed?

   This question includes both the assignment of optimal individual abatement levels and design of the mechanism that insures that those levels are actually delivered.

4. How will the implementation of the policy affect farms’ production markets?

   Once a policy is designed it is necessary to evaluate effects of the policy on related production markets to insure that a new policy does not have a negative effect on them. In other words, a welfare analysis of effects of a new policy should be performed.

These questions are analyzed and answered sequentially.

First, it is proposed to choose subsidies over taxes. This choice is justified by 1) custom (society is reluctant to regulate farming, but is in the
habit of subsidizing it), and 2) the chance to participate in a collective subsidy arrangement provides a significant incentive for farmers to participate in the mechanism introduced in this work.

Second, it is shown that the mechanism that solves this allocation problem generates quantity and price that is efficient for both individual polluters and the society.

Third, it is shown that the problem of achieving a level $A$ of abatement from the watershed at minimum cost can be formalized as a generalized principal-agent problem with both adverse selection (agents are able to conceal their type) and moral hazard (existence of hidden action). Roger Myerson (1982) first formalized this problem. Despite a body of research on this topic, a general solution to the problem has not yet been derived; however, there are many results on simplified versions of the principal-agent problem – with only the moral hazard or adverse selection aspect, or using a single agent. A solution to the generalized principal-agent problem under assumptions consistent with nonpoint source pollution is derived in this work.
Fourth, it is shown that under some conditions implementation of the designed policy will result in increase in social welfare.

The approach that is used in this study can be applied to other policy design problems. This approach is described in details in this dissertation.

The dissertation is organized as follows. Chapter 2 provides a review of the current literature on NPS and mechanism design, and previews the contributions of the study in literature. Chapter 3 provides a solution to the generalized principal-agent problem under assumptions consistent with the NPS pollution problem. In chapter 4, an algorithm for the policy-maker is described and a policy that can be used to efficiently regulate NPS pollution is designed. Chapter 5 summarizes the results and conclusions of this study.
Definitions of Terms

Nonpoint Source Pollution (NPS): pollution from diffuse sources, such that the emissions of several polluters may affect the ambient pollution levels and it is not possible to separate their contribution. Some authors have claimed also that NPS pollution is especially subject to uncertainty due to the effects of random variables on the relationship between treatments and effluents and the relationship between effluents and ambient levels of the pollution.

Principal-Agent Problem: a situation where one economic actor, called the principal, can set the rules under which another economic actor, called the agent, to maximize his utility chooses an action independently of the principal that nevertheless affects the principal’s utility; the agent’s utility function is different from that of the principal.

Adverse Selection Problem: a principal-agent problem in which the agent has private information about a parameter of his optimization problem (agent’s type).
Moral Hazard Problem: a principal-agent problem has a moral-hazard component when an agent can privately chose an action that is best for him, but is not optimal for the principal.

Generalized Principal-Agent Problem: a principal agent problem with multiple agents that has both moral hazard and adverse selection components.

A strategy strongly Dominates all other strategies of agent $i$ if the payoff to this strategy is strictly greater than the payoff to any other strategy, regardless of which strategy is chosen by the other agent(s).

A Dominant Strategy is the strategy that strongly dominates all other strategies available to the agent.

A Dominant Strategy Mechanism is the mechanism that achieves equilibrium, in which all agents chose dominant strategies.
CHAPTER 2

BACKGROUND

Nonpoint source pollution has several characteristics that make its regulation difficult. This kind of pollution is diffuse in nature so it is difficult to measure and monitor how much each nonpoint source discharges, and it depends on unpredictable events like weather. Consequently, instruments developed to control point source pollution are seldom effective in the nonpoint case.

Current policies

To control nonpoint pollution, federal and state agencies developed voluntary participation programs addressed to agricultural sources. Among
these, cost-sharing programs of various kinds have dominated since the
1980’s. Cost-sharing programs implemented by public agencies reimburse
nonpoint polluters for certain abatement expenses. In particular, farmers
are subsidized for installation of conservation practices or new waste
management structures on their farms that are expected to reduce off-site
effects of land management. Those practices are called “best management
practices”, or BMPs. Section 319 of the 1986 reauthorization of the Clean
Water Act authorizes EPA to spend approximately $130 million annually
on nonpoint sources. Between 1996 and 2002, the U.S. Department of
Agriculture distributed over $1.6 billion to farmers through the
Environmental Quality Incentive Program and the Habitat Incentive
Program. In Ohio, the Natureworks program provides $1.5 million per
year for different watershed projects that install BMPs (M. Taylor and B.
Sohngen, 1998).

While cost-sharing programs are very expensive, they are not as
effective as is desired. Typically, agencies determine programmatic
success by the number of different practices that were installed rather than
actual gains in water quality. As Tietenberg noted in 1985, even if cost-
sharing programs help improve water quality in certain watersheds, programs that focus on inputs rather on outputs are not likely to be the cheapest way to improve environmental quality.

Most existing cost-sharing programs are using a technology-based approach. That is, typically NPS programs subsidize particular technologies, often BMPs selected from a menu, but do not specify explicit abatement standards or targets that must be met. There are several reasons for this approach to NPS pollution control: the general reluctance to regulate or penalize agriculture explains the reliance on subsidies; and it is believed to be easier to monitor on farm compliance with BMPs than with abatement targets in the NPS context. Nevertheless, these programs can impose excess costs on both individual firms and society. Because there may be a more efficient method for the firm to use to achieve the same results, such as re-engineering the entire process, technology standards are not likely to minimize pollution abatement costs.

When they are feasible, performance-based approaches provide attractive alternatives to technology-based approaches. Performance-based approaches dictate only a level of pollution abatement, but not the
methods used by firms. Firms can choose whichever practices are most economical for them to meet the standard, and naturally they would choose the technology that minimizes their costs for reducing the specified amount of pollution.

Pollution permits trading is an example of a performance-based program designed for point sources. A specific number of pollution permits is distributed among potential polluters. Each permit allows its holder to discharge a fixed amount of pollution. A polluter is punished if he violates the assigned level of pollution. Economic theory predicts that if pollution permits trading is allowed then firms with high cost of abating their own emissions will purchase additional allowances from firms with low costs of abatement. The total number of permits does not change, so the total level of pollution from the group of firms does not increase.

However, the shift from technology-based to performance-based programs is likely to meet environmental quality targets at lower cost. The following example illustrates this claim.

Title IV of the Clean Air Act Amendments of 1990 initiated the sulfur dioxide trading program. It included only point source polluters.
Before the trading program was initiated, technology standards were applied to the pollution sources. Specifically, each source of sulfur dioxide was required to install scrubbers. The predicted marginal cost of sulfur dioxide reduction with scrubbers was over $1,000 per ton of sulfur dioxide in the 1980s. In the 1990s, after introduction of sulfur dioxide permit trading market, the price of permits for sulfur dioxide has been approximately $130 to $150 per ton. With the implementation of the trading market, firms are able to allocate abatement among themselves in more efficient manner: firms with low cost do more abatement then firms with high cost. Furthermore, as a precursor to trading, performance standards were implemented instead of traditional design standards: firms no longer had to install technology to “scrub” sulfur from emissions. They instead could substitute other forms of abatement, which included importing low sulfur coal from western states (Burtraw, 1996).

Several trading programs have been developed to include nonpoint source polluters. Those programs have been more complicated, given the various kinds of uncertainty associated with nonpoint sources. Given the difficulty of determining effluent pollution levels for nonpoint pollution
sources, NPS sources earn tradable permits by implementing BMPs. That is nonpoint sources offer not delivered abatement, but employment of abatement practices. Clearly the relation between used abatement practices and actual abatement levels is uncertain. In NPS trading programs the method most commonly employed for reducing the probability that NP sources will fail to deliver planned abatement is a trading ratio. This aims to provide a safety margin, much like a safe minimum standard (Ciriacy-Wantrup, 1968). The trading ratio credits a NP source with less abatement than predicted by technological models, in case the conservation practices turn out to be less effective than predicted. For example, a trading rule may require that a point source must purchase BMPs predicted to generate 3 tons of pollution reduction from a nonpoint source in order to earn 1 ton of pollution reduction credits.

Trading programs that include nonpoint sources as well as point sources were implemented in Dillon Reservoir, Colorado and in Tar-Pamlico River Basin, North Carolina. In the first case two point-nonpoint trades occurred, in second no trades have occurred yet. However all pollution sources remain well below their allowances. According to
engineering analyses, the point sources – when confronted with the explicit cost of buying permits – were able to implement cost-saving methods of pollution abatement in their own plants (EPA, 1996).

Although pollution-trading programs that include nonpoint sources have generated demonstrable efficiencies in PS abatement, on the NPS side they are still based on BMPs, not actual nonpoint sources’ performance. Consequently, they do not create incentives for farmers (or other nonpoint polluters) to search for new low cost abatement practices, and cannot be considered as efficient as performance-based programs should be. On the other hand, it is not easy to include nonpoint sources into performance-based trading programs since it is very costly or impossible to monitor their performance. As a result, point-nonpoint pollution-trading programs remain relatively few and it is hard to verify that these programs have generated much NPS abatement.

One persistent criticism of permit markets including nonpoint sources is that informational asymmetries lead to a moral hazard problem; i.e. farmers may misrepresent abatement efforts (Shortle and Dunn, 1986; Smith and Tomasi, 1999; Moledina et al., 2001). Many have examined
methods of monitoring and enforcement to address this issue (Russell et al., 1986; Malik, 1993; Garvie and Keeler, 1994; Van Egteren and Weber, 1996; Amacher and Malik, 1996, 1998; Hartford, 2000; Kaplan et al., 2001). Some economists argue that due to informational asymmetries, second-best (i.e. technology-based) mechanisms for regulating nonpoint pollution can achieve abatement more efficiently than can first-best, i.e. performance-based, mechanisms (Tsur and Dinar, 1997; Johansson, 2001).

Therefore, despite the importance of the problem, current NPS regulation policies are either very costly and inefficient (cost-sharing programs) or not working effectively enough (permits trading programs). In both cases there are little evidence of measurable reduction of nonpoint source pollution.

**Theoretical progress**

Economists have proposed a number of theoretical incentive-based instruments to control nonpoint source pollution.
The majority of those policies fall into two broad classes: (1) design-based incentives, and (2) performance-based incentives.

Since efficiency and cost effectiveness are not the only criteria for judging environmental policies, but other considerations may include overall effectiveness, ease of implementation, equity, information requirements, monitoring and enforcement capability, political feasibility, and clarity to the general public (R. Hahn and R Stavins, 1992), some economists argue that design-based incentives may be preferable to performance-based mechanisms (Tsur and Dinar, 1997; R. Johansson, 2001; and others).

Theoretical investigations have continued in both directions, and several new NPS policies and policy instruments have been proposed in recent decades.

*Design-based incentives*

Design-based incentives are based on a producer’s variable input use and production technology.
In the literature three different bases for such incentives are described:

- expected runoff;
- inputs;
- technology.

*Expected runoff*

Policies, based on expected runoff, are designed the following way. A resource management agency develops a model to simulate runoff from each agricultural cite, monitors input and technology use on each of these sites in order to derive some expectations about runoff. Then the resource management agency can design tax/subsidies scheme based on expected runoff that is similar to the one developed for point sources regulation.

However, expected runoff-based tax/subsidy schemes can be designed to achieve an efficient outcome only under very restrictive conditions. (Shortle, and others 1998). The main problem with this
approach is that designing expected runoff incentives is quite a complex task, and puts very high informational requirements on agencies.

*Input- and Technology-based incentives*

Examples of input-based incentives are taxes imposed on polluting inputs, such as fertilizers and pesticides, and subsidies for purchases of pollution control equipment.

Overall informational requirements as well as administration and enforcement costs are relatively low, which make such policies very attractive for implementation. In fact, policies based on input-based incentives have been used in several states. Several researchers have reported empirical analyses and policy simulations (Abrahams and Shortle, 1997; Babcock, 1997; Helfand and House, 1995; and others).

Although input-based and technology-based incentives may be relatively simple in implementation, they can achieve only less efficient outcomes than performance-based incentives. The reason is that the relation between pollution level, inputs, and technology used is very
uncertain and varies among nonpoint polluters (due to difference in landscape and production process). Therefore inputs and technology are very imprecise approximation for the runoff levels.

Performance-based incentives

The most logical targets of performance-based incentives are runoff from the field and ambient water quality. Theoretically, incentives based on runoff are most appealing since, in this case, the price for pollution can be applied directly to the polluter. Unfortunately, those policies are not feasible due to the diffuse nature of the nonpoint pollution; runoff from a particular firm cannot be monitored at a reasonable cost. This explains the lack of runoff-based policies in current literature.

Another possibility is ambient pollution based incentives. The regulator can measure the ambient concentration of pollution at some specific point in the river or the lake and determine the list of firms that potentially contributes. Then he can design a policy that aims to induce these contributors as a group to abate at some target level.
To be effective, ambient-based incentives should be designed so as to resolve the informational asymmetries characteristic of nonpoint pollution. Specifically, the regulator does not know the production process used by an individual farmer and the level of effort a farmer makes to reduce runoff from his farm. Those two types of asymmetric information in economic theory are called respectively adverse selection (or unknown type) and moral hazard (or unknown action). Situations where such problems exist are called principal-agent problems.

A principal-agent problem arises when there are two types of economic agents: one – principal – who sets the rules in the market and another – agents – who have to follow those rules. All agents have their specific objectives. Agents have private information about their types and they have the power to make private decisions about their actions. Adverse selection is a principal-agent problem in which the agent has private information about a parameter of his optimization problem (agent’s type). A principal-agent problem has a moral-hazard component when agents can make private decisions about their actions that might be not in best principal’s interests. The generalized principal-agent problem has both
adverse selection and moral hazard components and permits both multiple agents and multiple principals. Clearly, a nonpoint pollution problem corresponds to a generalized principal-agent problem, since both types of asymmetric information exist in NPS setting.

In the theoretical mechanism-design literature adverse selection and moral hazard first were investigated separately. The existing literature on mechanism design in the NPS setting continues to consider adverse selection and moral hazard separately.

**Adverse selection.**

To solve an adverse selection problem, the Principal must provide agents with incentives that could induce truthful revelation of their types.

Clarke (1971), Groves (1973), and Groves and Loeb (1975), making strong assumptions on preferences, provided mechanisms with monetary transfers (now called Groves transfers) inducing truthful revelation of preferences in the context of the provision of Public Goods. Later those mechanisms were developed by Green and Laffont (1979), Aspremont and Gerard-Varet (1979), and others.
Green and Laffont (1977) show that the Groves transfers are the only transfers that make truthful revelation a dominant strategy when no restriction is put on the domains $Q_i$ of agents' types. Another result of Green and Laffont is that, in general, no member of the Groves class satisfies budget balancing. Holmström 1979 has shown that when the domain of $Q_i$ is not smoothly connected (e.g., made of two disjoint closed intervals), there are dominant-strategy mechanisms that are not Groves mechanisms.

The principal-agent problem with only adverse selection cannot model the NPS case, since it assumes that firms’ effluent levels are known, which makes it a point source pollution case.

**Moral Hazard.**

To solve the Moral Hazard problem, the Principal must provide incentives, which could induce agents’ obedience in undertaking assigned actions. General treatments of moral hazard problem (without hidden knowledge) have been provided given by Grossman and Hart (1983), Mookherjee (1984), and Rogerson (1985).
Solow (1979), Salop (1979), and Shapiro and Stiglitz (1984) have shown that if the performance of the agent is not easy verifiable, contracts must use the threat of termination, combined with high wages as a disciplinary device instead of promising a share of profit to the agent. In multi-agent environments Mookherjee (1984), Nalebuff and Stiglitz (1983), and Green and Stockey (1983) have shown that the performance of an agent can be used to incentivize another agent if their performances are correlated, even if their efforts are technologically are unrelated. Holstrom (1982) designed a scheme that can correct a moral hazard problem in teams, which requires that each agent pay the full marginal damages of team shirking. Rasmusen (1987) proposed a stochastic system of fines to solve moral hazard problem in risk-averse teams.

Those results have been applied intensively to nonpoint pollution case.

An ambient tax-subsidy scheme similar to one designed by Holstrom (1982) was proposed by K. Segerson (1985), and then was further developed by R Cabe (1992), R Horan (1998), and others. The main idea of this kind of policy is that each nonpoint source of the
pollution would be charged (i.e. would have to pay a tax) for the total marginal social damage if the ambient pollution concentration level on surface and groundwater is greater than a policy target, and each nonpoint source would be rewarded (would receive a subsidy) if ambient level is lower than the target. In this setting, site-specific data on the pollution transport system and on the polluter’s beliefs regarding this system are required.

A P Xepapadeas (1991) applied Rasmussen’s (1987) random penalty scheme to NPS. In that setting, the government makes a specific kind of contract with polluters, which will be described next. If producers will reduce the ambient level of pollution, then each of them will receive a subsidy from an environmental agency. The amount of subsidies depends on the deviations between the target level (defined in the contract) and the measured level of ambient water pollution. When ambient standards are exceeded, one or more dischargers, selected randomly, are liable for a fine, while the rest receive subsidies.

Non-point tournaments, offered by Ramu Govindasamy, Joseph A. Herriges, and Jason F. Shogren (1994) provide a middle ground between
ambient tax and random penalty schemes. A nonpoint tournament uses readily available information on input or pollution abatement practices use to construct a relative ranking of the NPS polluters. Each source is then rewarded or penalized based solely on the ranking of its pollution abatement effort relative to the abatement effort of all other sources.

Since all those policies model NPS as a principal-agent problem with moral hazard only, it is common for all of them that the information requirement both for producers and regulation agencies is very high. Each producer needs information about the production and runoff characteristics of all producers, and about the transformation of runoff into ambient pollution. One more common feature is quite high overall complexity. In particular, a producer must be able to evaluate how he/she and others influence the incentive base. Monitoring cost is also expected to be high.

Another big problem of all these policies is political feasibility. The idea that one producer can be punished even if he/she is totally compliant, does not sound fair. This will cause problems with approval of policy based on the above-described mechanisms.
Generalized Agency Problem.

Due to the joint presence of adverse selection and moral hazard, the principal must now provide two types of incentives to the agents – to induce truthful revelation of the agents’ types and obedience in undertaking the action prescription allocated to this type. These incentives interact in nontrivial ways (Faynzilberg and Kumar 1995). Therefore results from basic agency literature may not always be applicable.

Faynzilberg and Kumar (2000) have shown that in the case of one agent under some other technical conditions on functional form of agents’ utility functions generalized principal–agent problem can be solved. A bivariate optimization problem - maximization of the principal’s utility with respect to both agent’s type and agent’s action, can be decomposed into two univariate variational problems - maximization of the principal’s utility, conditioned on an action, with respect to type (it is similar to a pure adverse selection problem); and maximization of principal’s utility, conditioned on optimal type, with respect to action (similar to a pure moral hazard problem). An optimal contract then could be derived from a sequence of two decision-making problems.
Because, Faynzilberg and Kumar (2000) have analyzed only the case with a single agent, their result is not applicable to the NPS problem.

Within the NPS literature, the adverse selection and moral hazard problems have not been treated simultaneously. As a result, the performance-based NPS abatement mechanisms proposed thus far by economists are not realistic.

Summary

Current NPS pollution control policies are either very costly and inefficient (cost-sharing programs) or not working effectively enough (permit trading programs). Theoretically-developed policies are either inherently inefficient (design-based) or not applicable since do not simultaneously solve the adverse selection and moral hazard problems (performance-based).
Contributions of this study.

This study offers a performance-based policy that can deal with asymmetric information. I show that under assumptions consistent with the NPS pollution situation it is possible to decompose the generalized principal-agent problem, the bivariate optimization problem, into two univariate variational problems in the multiagents case, and to design a two-step contract that solves both the adverse selection and the hidden action problems.

My strategy is to separate the adverse selection and moral hazard problems by delegating the distribution function from the regulator to the group of agents. The principal pays only for the group performance, which he can observe, and designs a payment schedule to deal with the adverse selection problem. Specifically, the price the regulator pays per unit of abatement is increasing in abatement. This kind of payment attracts low cost agents first, and only then agents with higher cost. The agents need to design a scheme for distributing payment inside the group, that deals with moral hazard.
I show that under the assumptions of the model it is possible to design an efficient distribution mechanism that can deal with moral hazard problem among agents. Useful properties of the mechanism are that it is in dominant strategies (i.e. works in both certainty and uncertainty cases) and budget balancing (i.e. total money transfer from the regulator is greater or equal to the sum of money transfers to agents). Although Green and Laffont (1977) have shown that Groves transfers are the only transfers that make truthful revelation in dominant strategies if there are no restrictions imposed on domain of agents’ types, and no member of the Groves class satisfies budget balancing condition, in this model with a strong restriction on the domain of agents’ types (they are singletons) it was possible to design a mechanism that is not Groves and is both in dominant strategies and budget balancing.

I show that this mechanism can be used to design a policy to regulate NPS pollution.
CHAPTER 3

ON THE GENERALIZED PRINCIPAL-MULTIPLE AGENTS PROBLEM

Formulation of the Problem within the NPS setting

The general formulation of the generalized principal-agent problem was given first by Myerson (1982). In the NPS setting it can be formulated as following.

There is a principal (regulator) and \( n \) agents (farmers).

Agent \( i \) can produce an abatement \( a_i \) with a cost of abatement \( C_i \) \((a_i)\). It is assumed in this study that the cost of the abatement function has the following form: \( C_i = \frac{1}{2} \alpha_i a_i^2 + \beta_i a_i \), where \( \alpha_i \) & \( \beta_i \) are deterministic parameters of the cost function and \( a_i \) is the abatement level, produced by
Agent $i$ (see Chapter 4 for justification of the choice of the functional form).

Agents’ actions are abatement levels, $d_i = a_i$. Neither Principal nor Agents except for the Agent $i$ can observe the Agent’s $i^{th}$ action. They only know that $\forall i\ a_i \in (0, \overline{a}_i)$. Therefore, the domain of Agent $i^{th}$ actions is $\forall i\ D_i = (0, \overline{a}_i)$. The regulator and farmers can observe though the total level of abatement $a = \sum_i a_i$.

Parameters of Agents’ cost of the abatement functions are referred as Agents’ types, that is $\theta_i = (\alpha_i, \beta_i)$. The principal knows only the realized distribution of $\alpha_i, \beta_i$ and that $\forall i\ \alpha_i \in (\overline{\alpha}; \overline{\alpha})$ & $\beta_i \in (\overline{\beta}; \overline{\beta})$, but he does not know which realization of parameters belongs to which agent. Therefore the domain of the Agent $i^{th}$ type for the Principal is $\forall i\ \Theta_i = (\overline{\alpha}; \overline{\alpha}) \otimes (\overline{\beta}; \overline{\beta})$. However in the model it is assumed that since farmers who are subjects to the policy live in the same watershed and produce similar products, they can observe each other’s types. Therefore, for each Agent $j$ the domain of the Agent $i^{th}$ type is a singleton:
∀i Θ, \( \theta_i = (\alpha_i, \beta_i) \). For the rest of the paper, the notations \( \theta_i \) and \( \{\alpha_i, \beta_i\} \) will be used interchangeably.

In this study, we restrict our attention to subsidy schemes; that is, the regulator has to pay for the abatement level. Justification for such a choice can be found in Chapter 4. Therefore, the Principal decision is the combination of a payment rule for the abatement \( T(a) \) and the distribution rule \( d_0 = t(a) = (t_i(a), \ldots, t_a(a)) \), where \( t_i \) is a money transfer to an Agent \( i \) from the Principal and \( t \) is the vector of money transfers to Agents from the Principal.

Agents are utility maximizers. Agents’ utility functions are their profit functions:

\[
u_i(t_i, a, \{\alpha_i, \beta_i\}_{i=1}^n) = \pi(t_i, a, \{\alpha_i, \beta_i\}_{i=1}^n) =
= t_i(a, \{\alpha_i, \beta_i\}_{i=1}^n)) - \left( \frac{1}{2} \alpha_i a_i^2 + \beta_i a_i \right) i = \{1, \ldots, k\} \]

The regulator’s objective is to achieve a level of abatement \( A \) with minimum cost. He can achieve his objective by designing a coordination mechanism \( \pi(t(a), (a_1, \ldots, a_n); \{\alpha_i, \beta_i\}_{i=1}^n) \), which describes agents’
payments rule as a function of agents’ reported types and agents’ reported actions, to induce optimal from his perspective agents’ behavior.

\[ \pi(t(a),(a_1,\ldots,a_n);\{\alpha_i,\beta_i\}_{i=1}^n) \]

is called a direct coordination mechanism iff each agent chooses to report his type truthfully and chooses action as the principal prescribes. It was shown by Myerson, 1982, that the principal can restrict his problem of designing an optimal mechanism to finding a direct mechanism. Therefore, the focus in this thesis is on designing of a direct mechanism.

**Optimal contract**

In the NPS setting the regulator has to design a coordination mechanism that can solve both adverse selection and moral hazard problems simultaneously. To solve this problem it is offered in the thesis to replace the bivariate problem (the combination of adverse selection and moral hazard) by two univariate sequential problems (considering adverse selection and moral hazard separately). This replacement is possible because, in the problem under consideration, the adverse selection
problem does not exist among agents; therefore, the principal can use their informational advantage and delegate some regulatory power to the group of agents. We will call such a group an Association.

In particular, the regulator pays for pollution reduction credits earned by the whole group of the farmers and is concerned only with the total level of the abatement achieved, while the group of farmers undertakes responsibility to distribute the payment so as to induce the farmers to deliver the desired level of abatement (see Figure 1). We show that it is possible to devise an optimal contract among members of the Association to deal with the farmers’ hidden action problem.

![Figure 1. Separation of the Adverse Selection and Moral Hazard Problems.](image-url)
Regulator – Association contract

The Regulator does not know which farmer produces which amount of abatement, but he knows that the whole group of farmers produces the level $a$. Therefore, if he can convince farmers to accept the payment for the total level of abatement as a group and distribute this payment among themselves, then he does not need to know individual contributions. In other words, he can state that those farmers, who want to produce the abatement and sell it to the Regulator, have to indicate it by joining the Association. The Regulator will buy the total level of abatement from the Association. It is now the Association’s problem to distribute individual payments among farmers. Basically, the Regulator delegates the distribution function to the Association, which has an informational advantage. With such an arrangement the Regulator does not face the “free-rider” problem.

However he still has to solve adverse selection problem, i.e. sign a contract with farmers with lowest among others cost.
In addition, to attract farmers to join the Association the regulator needs to meet the following conditions. He must:

1. create interdependence among farmers, i.e. make it profitable for the farmers to work as a group;

2. insure that the Association can work:
   a. show that there exist a mechanism, which solves the hidden action problem inside the Association;
   b. restrict the class of mechanisms to the dominant strategy mechanism, since the dominant strategy mechanism can work equally efficiently under certainty and uncertainty;
   c. correct for possible rent-seeking behavior inside the Association.

To solves the adverse selection problem and creates interdependence among farmers I offer to use a payment rule from the regulator to the Association such that the price for the abatement is increasing in total abatement.
Given such an offer, farmers are interested in attracting more new members into the Association, since more farmers are in the group, more abatement they can produce together, higher the price for the abatement is going to be, and each farmers expects to receive higher profit.

Contract with increasing in abatement price also solves the adverse selection problem. Only for farmers with lowest cost of abatement it is profitable to join the Association in the beginning, when the Association is just formed. Then as number of members of the Association is increasing and possible price for abatement is increasing, it is potentially profitable for farmers with higher cost of abatement to join the Association. For some farmers with very high cost of abatement it is not profitable to join the Association at all. The process of joining the Association is not analyzed in the thesis, but it is shown that only farmers with lowest cost will accept such a contract. Therefore, a contract with a price, increasing in abatement, solves adverse selection problem.

For simplicity we will choose a linear contract line:

$$P = \gamma a + \eta$$  \hspace{1cm} (3.1),

where $a$ – is a total abatement and $\gamma$ & $\eta$ are parameters.
An upward sloping contract curve gives the possibility of some sort of bargaining between the Regulators and the group of farmers – the Regulator gives farmers the opportunity to choose among all available technologies and effort levels. He is ready to pay only for the produced total level of abatement, but he agrees to pay a higher price for each next unit, so the marginal payment, i.e. price, rises with quantity produced. The group of farmers, called the Association, is choosing the level of abatement, and to maximize its profit the Association will produce at the point at which the marginal payment to the group of farmers is equal to the marginal cost \((\text{first-best})\).

With this kind of the payment rule the Regulator can control the number of the farmers in the Association. If parameters of the price line are small, farmers with low cost of abatement will join the program, but farmers with higher costs will want to stay out of the Association. With the increase of parameters of the price line farmers with high cost will want to participate. Therefore, the Regulator by varying parameters of his offer can “select” number of the participants in the program, and therefore influence the total level of abatement from the Association.
Furthermore, farmers’ decisions whether to produce abatement or not and how much abatement to produce, in addition to parameters of the contract offered by the regulator, depends on how total transfer from the regulator is distributed among members of the Association. The regulator from the payment rule and distribution rule can derive the “Association’s response” function – the level of abatement as a function of the parameters of his payment rule. Then the regulator can find optimal parameters of his payment rule that will induce farmers to produce a desired level of abatement A. Since farmers with lowest cost join the Association first, then the desired level of abatement will be produced with minimum cost.

Below we offer a contract that solves an Association’s distribution problem. Then we show how from such a contract the “Association’s response” function can be derived, and how the Regulator can choose the parameters of his offer to achieve the desired level of the abatement at minimum cost.

Association –Agents problem

In this part of the contract, the Association is considered as a principal, and the farmers as agents.
We consider two cases:

1. a benevolent principal, who wants to maximize the total transfer from the regulator to the Association, with utility

\[ u_0 = V_0(a, \{\alpha_i, \beta_i\}_{i=1}^n) = a(\gamma u + \eta) \], and

2. a self-interested Principal, who wants to maximize the Association’s surplus (i.e. the difference between total transfer from the regulator and sum of individual transfers to farmers), with utility

\[ u_0 = V_0(a, \{\alpha_i, \beta_i\}_{i=1}^n) - \sum_{i=1}^k t_i(a, \{\alpha_i, \beta_i\}_{i=1}^n) = a(\gamma u + \eta) - \sum_{i=1}^k t_i(a, \{\alpha_i, \beta_i\}_{i=1}^n). \]

We will say that:

- an allocation \((t(a), (a_1, \ldots, a_n); \{\alpha_i, \beta_i\}_{i=1}^n)\) is (ex post) efficient if

\[ \text{for each } \{\alpha_i, \beta_i\}_{i=1}^n \ a(\{\alpha_i, \beta_i\}_{i=1}^n) \text{ maximizes } \]

\[ \sum_{j=0}^k V_j(a, \{\alpha_i, \beta_i\}_{i=1}^n) = a(\gamma u + \eta) - \sum_{i=1}^k \left( \frac{1}{2} \alpha_i a_i^2 + \beta_i a_i \right), \text{ over } a_i, \]

\[ \forall i \& \{\alpha_i, \beta_i\}_{i=1}^n; \text{ (E)} \]
• an allocation \((t(a),(a_1,\ldots,a_n);\{\alpha_i,\beta_i\}_{i=1}^n)\) is implementable if there exists a transfer function \(t(\cdot)\) such that the allocation \((t(a),(a_1,\ldots,a_n);\{\alpha_i,\beta_i\}_{i=1}^n)\) for all \(\theta \in \left[\underline{\theta},\overline{\theta}\right]\) and for all \(\hat{\theta}_i\) satisfies the incentive-compatibility constraint

\[
\text{(IC)} \quad u_i(t,(a(\theta_i,\theta_\omega)),a(\theta_i,\theta_\omega);\theta_i) \geq u_i(t,(a(\hat{\theta}_i,\theta_\omega)),a(\hat{\theta}_i,\theta_\omega);\theta_i) \quad \text{for all } i
\]

• an allocation \((t(a),(a_1,\ldots,a_n);\{\alpha_i,\beta_i\}_{i=1}^n)\) is feasible if \(a\) is implementable through \(t\), and \(a_i\) is individually rational for all \(i\);

\[
\text{(IR)} \quad u_i(t,(a(\theta)),a(\theta),\theta) \geq u \quad \forall \theta,
\]

• an allocation \((t(a),(a_1,\ldots,a_n);\{\alpha_i,\beta_i\}_{i=1}^n)\) is feasible under budget balance if it in addition satisfies the BB constraint.

\[
\text{(BB)} \quad \sum_{i=1}^{k} t_i(a,\theta) \leq a(\gamma u + \eta) \quad \forall \theta
\]
• the mechanism is of “dominant strategy” if 
\[(t(a),(a_1,\ldots,a_n);\{\alpha_i,\beta_i\}_{i=1}^n)\] is such that, for each agent 
\[i = 1,\ldots,k\] and for each \(\theta_i,\theta_{-i},\hat{\theta}_i\) 
\[u_i(t_i(a(\theta_i,\theta_{-i})),a(\theta_i,\theta_{-i});\theta_i) \geq u_i(t_i(a(\hat{\theta}_i,\theta_{-i})),a(\hat{\theta}_i,\theta_{-i});\theta_i)\]
(DIC);

That is, each agent is induced to tell the truth whatever the other agents' reports (or actions—this is equivalent).

• The mechanism is the Bayesian if 
\[(t(a),(a_1,\ldots,a_n);\{\alpha_i,\beta_i\}_{i=1}^n)\] such that, for each agent 
\[i = 1,\ldots,k\] and for each \(\theta_i,\theta_{-i},\hat{\theta}_i\) 
\[(BIC) E_{\theta_{-i}}u_i(y(\theta_i,\theta_{-i}),\theta_i) \geq E_{\theta_{-i}}u_i(y(\hat{\theta}_i,\theta_{-i})\theta_i)\]

The goal of the regulator is to design a mechanism that is feasible, \textit{(ex post) efficient, implementable, and feasible under budget balance, i.e.} satisfies (IR), (E), (IC), and (BB).

Green and Laffont (1977) designed a class of mechanisms that satisfy (IR), (E), (IC), mechanisms that belong to that class are called now Groves mechanisms. They also have shown that, up to irrelevant transfers
t_i(·), the Groves mechanism transfers are the only transfers that make truthful revelation a dominant strategy when no restriction is put on the domains Q_i of agents' types. Another result of Green and Laffont is that, in general, no member of the Groves class satisfies BB. The BB condition is not essential, but still is very desirable in most cases. Later Holmström (1979) has shown that when the domain of q_i is not smoothly connected (e.g., made of two disjoint closed intervals), there are dominant-strategy mechanisms that are not Groves mechanisms. In this setting the domain of agents’ types is also very restricted, it is a singleton, and I will show that there exists a mechanism that is not Groves, and that satisfies all desirable constraints, i.e. satisfies (IR), (E), (IC), and (BB).

**Benevolent principal**

First we consider the case of a benevolent principal

\[ i.e., \quad u_0 = V_0(a, \theta) = a(\gamma a + \eta). \]

The only goal of the principal (i.e., the Association) is to maximize the payment received from the Regulator. Therefore, for now we are not concerned with his possible rent-seeking behavior.
Lets consider the contract of the form:

\[ t_i = (\alpha, a^*_i + \beta_i) \left( \text{Min} \left\{ a - \sum_{j \neq i} a^*_j; \left\| 2a^*_i \frac{k-1}{k} - \sum_{j \neq i} a^*_j - a \frac{k-2}{k} \right\| \right\} - \frac{\gamma a^*}{k} \right) \]

(3.2),

with following notation:

- \( k_i \) - number of members in the Association;
- \( t_i \) - \( i^{th} \) Farmer payment;
- \( a \) - The total level of pollution abatement;
- \( a_i \) - \( i^{th} \) Farmer level of pollution abatement;
- \( c_i \) - \( i^{th} \) Farmer cost of pollution abatement function;
- \( \alpha, \beta_i \) - Parameters of the cost of abatement function \( C_i(a) \);
- \( \pi_i \) - \( i^{th} \) Farmer profit function;
- \( \gamma, \eta \) - Parameters of Regulator’s payment rule.

In this case \( \{ a^*_i \}_{i=1,...,k} \) is the solution of the system of equations:

\[ 2 \times \gamma \times a + \eta = \alpha_i \times a_i + \beta_i \quad \forall i = 1,...,k. \]
It will be shown below that this contract satisfies (IR), (E), (IC), and (BB).

Term $-\frac{\gamma a^2}{k}$ ensures that BB holds at the optimum, that is, if $\forall i \ a_i = a_i^\ast$, then $\sum_{i=1}^{k} t_i(a_i^\ast) = a^\ast (\gamma a^\ast + \eta)$.

The term $\min \left\{ a - \sum_{j \neq i} a_j^\ast \left| 2 a^\ast \frac{k-1}{k} - \sum_{j \neq i} a_j^\ast - \frac{k-2}{k} \right| \right\}$ secures BB around the optimum. That is, if $a^\ast \neq a$, then $\sum_{i=1}^{k} t_i(a_i) < a(\gamma a + \eta)$, with

$$\min \left\{ a - \sum_{j \neq i} a_j^\ast \left| 2 a^\ast \frac{k-1}{k} - \sum_{j \neq i} a_j^\ast - \frac{k-2}{k} \right| \right\} = a - \sum_{j \neq i} a_j^\ast, \text{ if } a < a^\ast \text{ - in the case of underproduction}$$

and

$$\min \left\{ a - \sum_{j \neq i} a_j^\ast \left| 2 a^\ast \frac{k-1}{k} - \sum_{j \neq i} a_j^\ast - \frac{k-2}{k} \right| \right\} = 2 a^\ast \frac{k-1}{k} - \sum_{j \neq i} a_j^\ast - \frac{k-2}{k}, \text{ if } a > a^\ast \text{ - in the case of overproduction}.$$
the difference between the payment from the Regulator and sum of all transfers to farmers in the case if the total level of the abatement $a$ is less then the optimal level of abatement $a^*$ by $\Delta$; i.e.,

$$(a^* + \Delta)(\gamma(a^* + \Delta) + \eta) - \sum_{i=1}^{k} t_i(a^*_i + \Delta_i) = (a^* - \Delta)(\gamma(a^* - \Delta) + \eta) - \sum_{i=1}^{k} t_i(a^*_i - \Delta_i),$$

(3.3).

Those differences are represented on the figure 2 by the shaded areas.

Figure 2. Total transfer from the Regulator, total transfer to farmers, and total cost of abatement
Therefore, we can consider only the case of underproduction, and then apply this result to the case of overproduction.

If \( a < a^* \), then the transfer to agent \( i \) will be:

\[
t_i(a, a^*, \alpha_i, \beta_i) = (\alpha_i a^*_i + \beta_i) \left( a - \sum_{j \neq i} a^*_j \right) - \frac{\gamma a^{*2}}{k}, \forall i = 1, ..., k \tag{3.4}.
\]

Given this form of the transfer, the farmer’s utility-maximization problem is following:

\[
\text{Max}_{a_i} u_i(a_t, \theta) = V_i(a, \theta) + t_i(a, \theta) = (\alpha_i a^*_i + \beta_i) \left( a - \sum_{j \neq i} a^*_j \right) - \frac{\gamma a^{*2}}{k} - \left( \frac{1}{2} \alpha_i a^*_i^2 + \beta_i a_i \right);
\]

F.O.C.: \((\alpha_i a^*_i + \beta_i) - (\alpha_i a^*_i + \beta_i) = 0 \Rightarrow \alpha_i a^*_i + \beta_i = \alpha_i a^*_i + \beta_i \Rightarrow a_i = \frac{\alpha_i a^*_i + \beta_i}{\alpha_i} \Rightarrow a_i = a^*_i.

Let’s consider efficiency condition:

\[
\text{Max}_{a_i, i=1,...,k} \sum_{j=0}^{k} V_j(a, \theta) = a(\gamma a + \eta) - \sum_{i=1}^{k} \left( \frac{1}{2} \alpha_i a^*_i^2 + \beta_i a_i \right);
\]

\[
\text{F.O.C.: } 2\gamma a + \eta - \alpha_i a_i - \beta_i = 0, \forall i = 1, ..., k \Rightarrow 2\gamma a + \eta = \alpha_i a_i + \beta_i, \forall i = 1, ..., k.
\]

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The system of equations (3.6) has k equations and k unknowns; matrix of coefficients is not singular; and therefore the system has unique solutions. This solution is denoted as \( \{a_i^*\}_{i=1}^{k} \). Therefore, we can say that an allocation \((t(a), a(\theta); \theta)\) is (ex post) efficient, if it induces each farmer to choose \( a_i = a_i^* \).

From (3.5) we see that \( a_i = a_i^* \) is the solution to the farmers’ maximization problem, if they receive from the Association the transfer in the form (3.2). Thus transfer of the form (3.2) induces each farmer to choose \( a_i = a_i^* \), and therefore satisfies the efficiency condition. Note that agent \( i^{th} \) decision does not depend on other agents’ actions types. Therefore this mechanism is dominant strategy mechanism.

Lets assume that all farmers except the farmer \( i \) produced assigned level of abatement, i.e., \( a_j = a_j^*, \forall j \neq i \). Also lets assume that farmer \( i \) produced less then assigned level by \( \Delta_i \), i.e., \( a_i = a_i^* - \Delta_i \). Then we can rewrite the transfer function to the \( i^{th} \) agent as
\[t_i(a, a^*, \alpha_i, \beta_i) = \left(\alpha_i a_i^* + \beta_i\right) \left( a - \sum_{j \neq i} a_j^* \right) - \frac{\gamma a_i^{*2}}{k} =
\]
\[(3.7) = \left(\alpha_i a_i^* + \beta_i\right) \left( a_i^* - \Delta_i + \sum_{j \neq i} a_j^* - \sum_{j \neq i} a_j^* \right) - \frac{\gamma a_i^{*2}}{k} =
\]
\[= \left(\alpha_i a_i^* + \beta_i\right) \left( a_i^* - \Delta_i \right) - \frac{\gamma a_i^{*2}}{k}
\]

Therefore, the \(i^{th}\) agent will be punished for underproduction by
\[
\left(\alpha_i a_i^* + \beta_i\right) \Delta_i
\]

Now let's see what will happen with the \(j^{th}\) agent payment when the \(i^{th}\) agent underproduces:

\[t_j(a, a^*, \alpha_j, \beta_j) = \left(\alpha_j a_j^* + \beta_j\right) \left( a - \sum_{k \neq j} a_k^* \right) - \frac{\gamma a_j^{*2}}{k} =
\]
\[(3.8) = \left(\alpha_j a_j^* + \beta_j\right) \left( a_j^* + \sum_{k \neq j, k \neq i} a_k^* + a_i^* - \Delta_j - \sum_{k \neq j} a_k^* \right) - \frac{\gamma a_j^{*2}}{k} =
\]
\[= \left(\alpha_j a_j^* + \beta_j\right) \left( a_j^* - \Delta_j \right) - \frac{\gamma a_j^{*2}}{k}
\]

So, all other agents are also punished for the \(i^{th}\) agent underproduction by the \(\left(\alpha_j a_j^* + \beta_j\right) \Delta_j\).

Note that \(\alpha_j a_j^* + \beta_j = \alpha_i a_i^* + \beta_i = 2\gamma a^* + \eta \forall i \& j = 1, ..., k\). That means that transfers to each farmer is reduced by equal amount. If agent \(i\)
underproduceceed, then his cost will be less, therefore his profit will be
reduced by only $\alpha_i a_i^* \Delta_i$, and all other agents’ profits will be reduced by
$(2\gamma a^* + \eta)\Delta_i$. That is, the proposed mechanism is the kind of mechanism
with collective punishment – if one is at fault, all must bear the
responsibility. Given such an incentives scheme, one would expect that
members of the Association will create some kind of the monitoring
among members. However, this issue is not addressed in this paper.

The case of the overproduction is symmetric – if one agent in the
group overproduces, again everybody will be punished equally.

If several members of the group deviate from assigned level, then
each member of the group will be underpaid by $(2\gamma a^* + \eta)\Delta$, where

$$\Delta = \sum_{i=1}^{k} \Delta_i.$$ 

The difference between payment from the Regulator to the
Association and sum of the transfers to agents is $(2\gamma a^* + \eta)\Delta|k \ \forall \Delta$. It
is always positive. That means that BB holds for any allocation.

The fact that constraints IC and IR also hold is proven in the
APPENDIX A.
To understand how each farmer is paid in the case when all members of the Association produce optimal abatement, we rewrite the payment \( t_i \) in the form: 
\[
t_i = (\gamma a^* + \eta)a^*_i + \gamma a^*(a^*_i - \frac{a^*}{k}).
\]
Therefore, the contract the Association creates is such that: total payment is the sum of “payment for absolute performance” - \((\gamma a^* + \eta)a^*_i\), the price of level of pollution times the amount by which the \(i^{th}\) farmer reduces pollution, and of the “payment for relative performance” - \(\gamma a^*(a^*_i - \frac{a^*}{k})\), the marginal change in price times the difference between farmer \(i\)’s performance and the average performance in the group. Each farmer benefits from any decrease of the cost by any other member of the Association. Therefore farmers have incentives to share their cost-decreasing innovations.

**Self-interested principal.**

The case of the self-interested Principal is somewhat more complicated. The Principal collects the surplus, i.e. the difference between total payment from the Regulator and sum of all transfers to agents. This
difference is positive if any of the agents produced other then optimal abatement. Therefore, the principal may want to bribe an agent to misproduces, and keep the surplus.

Lets assume that the principal offers a bribe $b_i(\Delta_i)$ to the farmer $i$ for producing $a_i^* - \Delta_i$. For the principal it does not matter whether the agent is going to produce more or less, but for the farmer it costs more to produce more, and it costs less to produce less, so he will choose the latter. If the farmer $i$ chooses to produce $a_i^* - \Delta_i$, then the transfer he will receive will be $t_i(\Delta_i) = (\alpha, a_i^* + \beta_i)(a_i^* - \Delta_i) - \frac{\gamma a_i^{*2}}{k}$, and his profit loss will be:
\[ \pi_i^* - \pi_i(\Delta_i) = (t_i^* - C_i^*) - (t_i(\Delta_i) - C_i(\Delta_i)) = \]
\[ = \left( \alpha_i a_i^* + \beta_i \right)(a_i^* - \frac{\gamma a_i^{*^2}}{k}) - \left( \frac{1}{2} \alpha_i a_i^{*^2} + \beta_i a_i^* \right) - \]
\[ - \left( \alpha_i a_i^* + \beta_i \right)(a_i^* - \Delta_i) - \frac{\gamma a_i^{*^2}}{k} - \left( \frac{1}{2} \alpha_i (a_i^* - \Delta_i)^2 + \beta_i (a_i^* - \Delta_i) \right) \]
\[ = \left( \alpha_i a_i^* + \beta_i \right) \Delta_i - \left( \frac{1}{2} \alpha_i \left( a_i^{*^2} - (a_i^* - \Delta_i)^2 \right) + \beta_i \Delta_i \right) \]
\[ = \alpha_i a_i^* \Delta_i - \left( \frac{1}{2} \alpha_i \left( a_i^{*^2} - a_i^{*^2} + 2a_i^* \Delta_i - \Delta_i^2 \right) \right) = \]
\[ = \alpha_i a_i^* \Delta_i - \alpha_i a_i^* \Delta_i + \frac{1}{2} \alpha_i \Delta_i^2 = \frac{1}{2} \alpha_i \Delta_i^2 \]

That means that minimal bribe (i.e., just to compensate the farmer for his loss) is

\[ \min b_i(\Delta_i) = \frac{1}{2} \alpha_i \Delta_i^2 \] (3.10).

It follows that if the principal pays \( b_i \), then the farmer will deviate from the optimal level of abatement at maximum by

\[ \Delta_i = \sqrt{\frac{2b_i}{\alpha_i}} \] (3.11).

Assume that only the agent who was bribed will produce differently from the optimal level of abatement, i.e., \( \Delta = \Delta_i \). Then
principal’s utility depend on the deviation from the optimal level as following:

\[(3.12)\]

\[u_i = a(\Delta)(\gamma a(\Delta) + \eta) - \sum_{i=1}^{k} t_i(\Delta) - b_i(\Delta) = \left(b_i = \frac{1}{2} \alpha_i \Delta^2\right) = \]

\[= (a^* - \Delta)(\gamma (a^* - \Delta) + \eta) - \sum_{i=1}^{k} \left(\alpha_i a^* + \beta_i\right)(a^*_i - \Delta) - \gamma a^2_k - \frac{1}{2} \alpha_i \Delta^2 = \]

\[= \left(\alpha_i a^* + \beta_i = 2\gamma a^* + \eta, \forall i \right) = \]

\[= (a^* - \Delta)(\gamma (a^* - \Delta) + \eta) - (2\gamma a^* + \eta)\sum_{i=1}^{k} a^*_i + (2\gamma a^* + \eta)\Delta k + \gamma a^2_k - \frac{1}{2} \alpha_i \Delta^2 = \]

\[= a^*(a^* + \eta) - (2\gamma a^* + \eta)\Delta + \gamma \Delta^2 - (2\gamma a^* + \eta)a^* + (2\gamma a^* + \eta)\Delta k + \gamma a^2_k - \frac{1}{2} \alpha_i \Delta^2 = \]

\[= a^*(2a^* + \eta)a^* + (2\gamma a^* + \eta)(k-1)\Delta + \gamma \Delta^2 - \frac{1}{2} \alpha_i \Delta^2 = \]

\[= (2\gamma a^* + \eta)(k-1)\Delta + \left(\gamma - \frac{1}{2} \alpha_i\right)\Delta^2 = (2\gamma a^* + \eta)(k-1)\Delta - \frac{1}{2} (\alpha_i - 2\gamma) \Delta^2 \]

That means that principal’s utility is equal to zero if \(\Delta = 0\) or

\[\Delta = \frac{2(2\gamma a^* + \eta)(k-1)}{(\alpha - 2\gamma)} \quad (3.13). \]

(Here we have to assume that condition \(\alpha_i > 2\gamma\) holds \(3.14\). Why this condition holds is discussed in the APPENDIX B.) Since utility function is continuous in \(\Delta\), then it has to
have the same sign for all $\Delta \in \left\{ \frac{2(2\gamma a^* + \eta)(k-1)}{(\alpha - 2\gamma)} \right\}$ and the same sign for all $(\Delta \in \left\{ \frac{2(2\gamma a^* + \eta)(k-1)}{(\alpha - 2\gamma)} \right\}; \infty)$.

Then the principal problem is

$$\begin{align*}
\text{Max } & u_0(\Delta) = (2\gamma a^* + \eta)(k-1)\Delta - \frac{1}{2}(\alpha_i - 2\gamma)\Delta^2 \Rightarrow \\
\text{F.O.C.:} & \quad (2\gamma a^* + \eta)(k-1) - (\alpha_i - 2\gamma)\Delta = 0 \Rightarrow \\
(3.15) & \quad \Delta = \frac{(2\gamma a^* + \eta)(k-1)}{(\alpha_i - 2\gamma)}; \\
\text{S.O.C.:} & \quad \frac{\partial^2}{\partial \Delta^2} u_0(\Delta) = -(\alpha_i - 2\gamma) < 0
\end{align*}$$

Therefore maximum of the $u_0(\Delta)$ lays in the interval

$$\Delta \in \left\{ 0; \frac{2(2\gamma a^* + \eta)(k-1)}{(\alpha - 2\gamma)} \right\}.$
(3.16)

\[
u_0 \left( \frac{(2\gamma a^* + \eta)(k-1)}{(\alpha_i - 2\gamma)} \right) =
\]

\[
= (2\gamma a^* + \eta)(k-1) \frac{(2\gamma a^* + \eta)(k-1)}{(\alpha_i - 2\gamma)} - \frac{1}{2}(\alpha_i - 2\gamma) \left( \frac{(2\gamma a^* + \eta)(k-1)}{(\alpha_i - 2\gamma)} \right)^2
\]

\[
= \frac{(2\gamma a^* + \eta)^2 (k-1)^2}{(\alpha_i - 2\gamma)} - \frac{1}{2} \frac{(2\gamma a^* + \eta)^2 (k-1)^2}{(\alpha_i - 2\gamma)} = \frac{1}{2} \frac{(2\gamma a^* + \eta)^2 (k-1)^2}{(\alpha_i - 2\gamma)} > 0
\]

Therefore, for all \( \Delta \in \left( 0; \frac{2(2\gamma a^* + \eta)(k-1)}{(\alpha - 2\gamma)} \right) \) \( u_0(\Delta) > 0 \). Which means that the principal can collect rent by bribing an agent to underproduce. On the Figure 3 gray area represents the rent that the principal can collect.

To solve this problem, the Association can introduce a “security deposit”. At the beginning of the period all members of the Association deposit a certain amount of money \( d_j, \forall j = 1, ..., k \) in the bank, so neither the principal nor agents can use it. At the end of the period, if the Association produced the scheduled level of abatement, then these deposits are returned to the agent; otherwise these money remains in the bank until next period. That means that the principal, if he wants to bribe
somebody, needs to compensate for the loss of the security deposit as well. So he will need to pay the agent $j$: 

$$b_j^* = b_j + d_j = \frac{1}{2}\alpha_j \Delta^* + d_j \quad (3.17).$$

This additional payment will shift the line that represents the total transfer from the principal to the agents upwards. Rent can then be collected only if the agent who was bribed underproduces by $\Delta^*$, where

$$\Delta^* = \frac{(2\lambda a^* + \eta)(k-1)}{(\alpha_j - 2\gamma)} - \sqrt{\frac{(2\lambda a^* + \eta)^2(k-1)^2 - 2d_j}{(\alpha_j - 2\gamma)^2}} - \frac{2d_j}{(\alpha_j - 2\gamma)} \quad (3.18).$$

$\Delta^*$ is a solution to the following problem:

$$u_o(\Delta) = (2\gamma a^* + \eta)(k-1)\Delta - \frac{1}{2}(\alpha_j - 2\gamma)\Delta^* - d_j = 0 \quad (3.19).$$

The security deposit should not be set higher than the expected profit. Since the mechanism is the dominant strategy mechanism, the expected profit is the profit at optimum $\pi^* = \pi(a^*)$. 

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That is

$$\pi_j(a^*) = (\alpha_i a_i^* + \beta_i) a_i^* - \frac{\gamma a^{*2}}{k} - \left(\frac{1}{2} \alpha_i a_i^{*2} + \beta_i a_i^*\right) - d_j =$$

$$= \frac{1}{2} \alpha_i a_i^{*2} - \frac{\gamma a^{*2}}{k} - d_j \geq 0 \Rightarrow$$

$$\Rightarrow d_j \leq \frac{1}{2} \alpha_i a_i^{*2} - \frac{\gamma a^{*2}}{k}$$

Figure 3. Change in the contract to correct the rent-seeking behavior
Note, that the higher the security deposit, the wider the interval in which the principal cannot collect any rent, so we choose to set the security deposit to be equal to his upper bound:

\[ d_j = \frac{1}{2} \alpha_j a_j^* - \frac{\gamma a_j^*}{k} \]  

(3.21).

Since the principal wants to pay the minimal possible bribe, he needs to find to whom he can pay the least:

\[ b_j^* = \frac{1}{2} \alpha_j \Delta^2 + d_j = \frac{1}{2} \alpha_j \Delta^2 + \frac{1}{2} \alpha_j a_j^* - \frac{\gamma a_j^*}{k}. \]

Since \(\alpha_j a_j^* + \beta_j = 2\gamma u + \eta\), then \(a_j^* = \frac{2\gamma u + \eta - \beta_j}{\alpha_j}\).

Then \(b_j^* = \frac{1}{2} \Delta^2 + \frac{1}{2} \alpha_j \left( \frac{2\gamma u + \eta - \beta_j}{\alpha_j} \right)^2 - \frac{\gamma a_j^*}{k}\);

\[ \frac{\partial}{\partial \alpha_j} b_j^* = \frac{1}{2} \Delta^2 + \frac{1}{2} \alpha_j \left( \frac{2\gamma u + \eta - \beta_j}{\alpha_j} \right)^2 + \frac{2}{2} \alpha_j \frac{2\gamma u + \eta - \beta_j}{\alpha_j} \left( \frac{2\gamma u + \eta - \beta_j}{\alpha_j} \right)^2 \]

\[ = \frac{1}{2} \Delta^2 + \frac{1}{2} \left( \frac{2\gamma u + \eta - \beta_j}{\alpha_j} \right)^2 - \frac{2\gamma u + \eta - \beta_j}{\alpha_j} \frac{2\gamma u + \eta - \beta_j}{\alpha_j} \]

\[ = \frac{1}{2} \Delta^2 - \frac{1}{2} \left( \frac{2\gamma u + \eta - \beta_j}{\alpha_j} \right)^2. \]

Since \(a_j^* = \frac{2\gamma u + \eta - \beta_j}{\alpha_j}\), then \(\frac{\partial}{\partial \alpha_j} b_j^* = \frac{1}{2} \Delta^2 - \frac{1}{2} a_j^* = \frac{1}{2} (\Delta^2 - a_j^*). \)

(3.22)
Since deviation from the optimal level cannot exceed the optimal level, the bribe is decreasing in $\alpha_j$.

\[
\frac{\partial}{\partial \beta_j} b_j^* = \frac{2}{\alpha_j} \left( \frac{2\gamma + \eta - \beta_j}{\alpha_j} \right) \left( -\frac{1}{\alpha_j} \right) = \frac{-2\gamma + \eta - \beta_j}{\alpha_j} = -a_j^* \quad (3.23).
\]

So bribe is decreasing in $\beta_j$ also. That means that the minimal bribe is to be paid to the farmer with highest parameters of the cost function. The last farmer to join the Association is a “marginal member” – his profit is equal to zero, so he is indifferent between joining in the Association and not joining.

\[
\pi_k^*(a_k^*) = (\alpha_k a_k^* + \beta_k) a_k^* - \frac{\gamma a_k^*}{k} = 0 \Rightarrow
\]
\[
\Rightarrow a_k^* = \frac{\gamma a_k^*}{k(\alpha_k a_k^* + \beta_k)} \quad (3.24).
\]

Substitute the expression (3.24) into (3.21) and then into (3.17), to get

\[
b_k^* = \frac{1}{2\alpha_k} \Delta^2 + \frac{\alpha_k}{2k} \left( \frac{\gamma a_k^*}{2(2\gamma a_k^* + \eta)} \right)^2 - \gamma a_k^{*2} \frac{\Delta^2 + \left( -\frac{\gamma a_k^*}{k(2\gamma a_k^* + \eta)} \right)^2}{2} - \gamma \frac{a_k^{*2}}{k}.
\]

(3.25)
From equations (3.18), (3.19), and (3.25), it is possible to find $\Delta^*$, the deviation from the optimum, starting from which the principal can collect the rent. Therefore, for small deviation $\Delta \leq \Delta^*$, the principal cannot collect any rent.

In order to ensure that the principal would not try to induce a larger deviation, $\Delta > \Delta^*$, an additional penalty can be introduced in the following form: if $\Delta > \Delta^*$ then the transfer to each farmer decreases by additional penalty $p_j$. Then the regulator will have to pay even higher bribe to an agent, and the cost for the regulator of obtaining the deviation $\Delta$ will be again higher than the gain from deviation $\Delta$.

Therefore, the contract of the form (3.2) can be easily modified so it will correct possible rent-seeking behavior inside the Association.

*Determinations of parameters from the regulator's problem*

Recall that the regulator has to achieve the level of the abatement $A$ with minimum cost. His minimization problem is constraint by participation constraint, i.e., for each set of parameters $\gamma$ & $\eta$ a specific
number of farmers will decide to join the Association; and by the Association’s response constraint, i.e., for each set of parameters $\gamma$ & $\eta$ a specific level of abatement will be produced by the Association. In other words the regulator’s problem is:

$$\begin{align*}
\min_{\eta, \gamma} & \quad a(\gamma a + \eta) \\
\text{s.t.} & \quad (1) \text{ participation constraint; } \\
& \quad (2) \text{ the Association’s response constraint; } \\
& \quad (3) \ a = A.
\end{align*}$$

The Association’s response constraint should show how much of abatement will be produced for each set of parameters $\gamma$ & $\eta$. From the Section above, it is known that Association will choose $a$ such that condition $\alpha_i a_i + \beta_i = 2\gamma a + \eta$, where $a = \sum_{i=1}^{i} a_i$ holds $\forall i (3.26)$. 

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\[ \alpha_i a_j + \beta_i = 2 \gamma a + \eta, \text{ where } a = \sum_{i=1}^{k} a_i \Rightarrow \]
\[ a_i = \frac{2 \gamma a + \eta - \beta_i}{\alpha_i} \Rightarrow \]
\[ \sum_{i=1}^{k} a_i = \sum_{i=1}^{k} \frac{2 \gamma a + \eta - \beta_i}{\alpha_i} \Rightarrow \]
\[ a = 2 \gamma \sum_{i=1}^{k} \frac{1}{\alpha_i} + \eta \sum_{i=1}^{k} \frac{1}{\alpha_i} - \sum_{i=1}^{k} \frac{\beta_i}{\alpha_i} \Rightarrow \]
\[ \begin{cases} \sum_{i=1}^{k} \frac{1}{\alpha_i} = \lambda, \text{ and } \sum_{i=1}^{k} \frac{\beta_i}{\alpha_i} = \mu \end{cases} \Rightarrow \]
\[ a = 2 \gamma \lambda + \eta \lambda - \mu \Rightarrow \]
\[ a = \frac{\eta \lambda - \mu}{1 - 2 \gamma \lambda} \]

Therefore, the regulator knows that, if he sets parameters \( \gamma \) and \( \eta \), then the Association will produce \( a = \frac{\eta \lambda - \mu}{1 - 2 \gamma \lambda} \), where \( \lambda \) and \( \mu \) are parameters, which characterize the whole group of farmers in the watershed.

The participation constraint should ensure that exactly \( k \) farmers decide to join the Association. Assume that there are many farmers in the watershed. Let’s rank-order them by their cost functions. That means that \( \alpha_1 < \alpha_2 < \ldots < \alpha_i < \ldots < \alpha_n \) and \( \beta_1 < \beta_2 < \ldots < \beta_i < \ldots < \beta_n \). Each farmer is going to
produce \( a_i^* \) such that \( \alpha_i a_i^* + \beta_i = 2\gamma a^* + \eta \). Then the last farmer (with highest cost of abatement), who decide to join the Association is going to be marginal – for him it does not matter whether he is in the Association or not. That means that \( \pi_k(a_k^*) = t_k(a_k^*) - C_k(a_k^*) = 0 \). Therefore, the following condition must hold:

\[
\pi_k(a_k^*) = (\alpha_k a_k^* + \beta_k) \left( \text{Min} \left\{ a^* - \sum_{j \neq k} a_j^*; 2a^* - a^* - \sum_{j \neq k} a_j^* \right\} \right) - \frac{\gamma a^{*2}}{k} - \frac{1}{2} \alpha_k a_k^{*2} - \beta_k a_k^* = 0
\]

\[
\Rightarrow (\alpha_k a_k^* + \beta_k) a_k^* - \frac{\gamma a^{*2}}{k} - \frac{1}{2} \alpha_k a_k^{*2} - \beta_k a_k^* = 0
\]

\[
\Rightarrow \frac{1}{2} \alpha_k a_k^{*2} - \frac{\gamma a^{*2}}{k} = 0
\]

\[
\Rightarrow 2\gamma a^{*2} = k\alpha_k a_k^{*2} \Rightarrow \gamma = \frac{k\alpha_k a_k^{*2}}{2a^{*2}}
\]

Since \( \alpha_k a_k^* + \beta_k = 2\gamma a^* + \eta \), then \( a_k^* = \frac{2\gamma a^* + \eta - \beta_k}{\alpha_k} \)

\[
\Rightarrow \gamma = \frac{k(2\gamma a^* + \eta - \beta_k)^2}{2a^{*2}\alpha_k}
\]

(3.27).

Substitute the total level of abatement from the Association’s response constraint

\[
a^* = \frac{\eta \lambda - \mu}{1 - 2\gamma \lambda}, \text{ where } \lambda^k = \sum_{i=1}^k \frac{1}{\alpha_i} \text{ and } \mu^k = \sum_{i=1}^k \frac{\beta_i}{\alpha_i}
\]

(3.28).
Then, if the following condition holds, there are exactly \( k \) farmers in the Association:

\[
2 \gamma \alpha_k \left( \frac{\eta \lambda - \mu}{1 - 2 \gamma \lambda} \right)^2 = k \left( 2 \gamma \left( \frac{\eta \lambda - \mu}{1 - 2 \gamma \lambda} \right) + \eta - \beta_k \right)^2 
\]

(3.29).

The regulator’s problem can now be rewritten as the following:

\[
\min_{\gamma, \eta} (\gamma a + \eta) \\
\text{s.t.} \quad (1) \ 2 \gamma \alpha_k \left( \frac{\eta \lambda - \mu}{1 - 2 \gamma \lambda} \right)^2 = k \left( 2 \gamma \left( \frac{\eta \lambda - \mu}{1 - 2 \gamma \lambda} \right) + \eta - \beta_k \right)^2 
\]

(3.30).

(2) \( a = \frac{\eta \lambda - \mu}{1 - 2 \gamma \lambda} \)

(3) \( a = A \)

The regulator’s problem can be solved the following way. First, one needs to solve the constraints. The solution to this system of equations is the optimal \( \gamma^k \) & \( \eta^k \) for each \( k \)-number of members in the Association. Therefore, \( \gamma^k \) & \( \eta^k \) can be considered as functions of \( k \). The exact solution for optimal \( \gamma^k \) & \( \eta^k \) is given in APPENDIX B.

Second, one has to substitute optimal \( \gamma^k \) & \( \eta^k \) into the objective function and solve for the optimal number of members in the Association:

\[
(3.31) \quad \min_k A(\gamma^k A + \eta^k). 
\]

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The solution to this part of the problem depends on the distribution of parameters of cost of abatement functions.

**Summary**

We have demonstrated that the Generalized Principal-Agents problem under restrictions, consistent with NPS setting, can be solved through decentralization, by using the informational advantage of agents, and that the optimal contract can be designed to achieve an efficient allocation.

Our solution to this problem calls for the regulator to contract for output to be produced by a group of farmers, paying for the total performance achieved by the group according to the rule: \( a(\gamma + \eta) \). The responsibility for distributing the payment and encouraging agents to deliver performance is vested in the group of agents (called the Association), an arrangement that utilizes the informational advantages that agents enjoy. The money inside the Association should be distributed according to the rule:
\[ t_i = (\alpha, a_i^* + \beta_i \left( \min \left\{ a - \sum_{j \neq i} a_j^* : 2a \frac{k-1}{k} - \sum_{j \neq i} a_j^* - a \frac{k-2}{k} \right\} \right) - \frac{k \gamma^2}{k}. \]

This contract is a two-level contract that separates adverse selection and moral hazard problems and solves them individually.

Our work demonstrates that agents willing to accept joint responsibility for performance (i.e., to join the Association), would enjoy cost-savings in the production process.

Another important feature of the solution is that it can work in the presence of production uncertainty as well as under certainty. In the case of uncertainty there is no risk sharing; all risk is put on agents, and the regulator pays only for the realized performance.

A useful property of the proposed here mechanism is that it is budget balancing. This property gives the mechanism an advantage before Groves mechanisms since no member of the Groves mechanisms satisfies budget balancing condition. Although Green and Laffont (1977) have shown that Groves transfers are the only transfers that make truthful revelation a dominant strategy if there is no restrictions are imposed on the domain of agents’ types, it is demonstrated that under restrictions on the
domain of agents’ types imposed in the model (agents’ types are singleton), it is possible to design a dominant strategy mechanism, which is not Groves, to resolve the moral hazard problem.

This problem was considered in, and the mechanism was designed for, a static setting. In order to achieve an efficient allocation, the regulator needs to know the distribution of the parameters of the abatement cost functions for farmers in the watershed. In a dynamic setting, the regulator can change the parameters of his contract line and observe the group response, thereby learning over time about costs of abatement for farmers in the watershed. This learning-by-doing approach might decrease the informational requirement for the regulator, and make the proposed solution even more tractable in practice, however this question is not addressed in this thesis and may be possible topic for a future research.

In Chapter 4 we will use the contract presented in Chapter 3 to design an effective policy to resolve Nonpoint Source Pollution Problem. Since the contract deals with both types of Asymmetric information – Moral Hazard and Adverse Selection – a policy, based on it, is going to be
more efficient under weaker informational requirement then other policies intended to control NPS.
CHAPTER 4

TRANSACTION CHAIN APPROACH TO NONPOINT SOURCE WATER POLLUTION PROBLEM

This chapter is devoted to the problem of a policy design.

Any policy’s goal is to change existing undesirable market conditions and move market to a desired equilibrium. Questions are: what equilibrium is desirable, how to achieve it at minimum cost, and who has to pay expenses. Those questions are connected: an answer to one question affects answers to others.

In this chapter I suggest an algorithm, which I will call the Transaction Chain Approach (TCA), that clarifies interrelations among these questions and helps a policy-maker answer them. In the first section of the chapter the approach itself is presented, in the second it will be applied to the nonpoint pollution control problem.

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The Transaction Chain Approach can be considered a way of reformulating a policy design problem to clarify and systematize the regulator’s search for a policy solution.

TCA is based on the following ideas. A typical market transaction consists of three separate steps: (1) assignment of property rights or initial endowment; (2) price/quantity determination; and (3) optimal design of the exchange process. Figure 4 illustrates this idea.
Figure 4. Transaction chain.

For a transaction to be completed it should go through all three steps in order, as rings in the chain (see the Figure 4). This gave the name to the approach. A policy maker can manipulate the outcome of the market by using specific policy tools at each step of the market transaction.

To design a policy that achieves an efficient outcome in the general equilibrium sense (GE-opt) can be technically a very difficult problem. If this is the case, then a policy-maker can benefit from focusing on designing a policy that achieves an optimal outcome in one specific market and therefore is efficient in terms of partial equilibrium (PE-opt). Given that PE-opt policy is not necessarily GE-optimal, a policy maker
needs to evaluate welfare effects of a PE-opt policy on related markets. If those effects are significantly negative, then he needs to make a choice: to work on a design of a policy that targets several markets simultaneously, or accept that he needs to bear some losses due to technical difficulty in getting the GE-opt solution.

The choice of a specific policy instrument for each of three steps of a transaction, combined with a welfare analysis of the GE effects of a PE-opt policy, form a four-step algorithm for a policy-maker.

At the first step, a property rights or initial endowment assignment basically answers the question of who will pay for the policy implementation. If an actor has a right to his baseline position, society will have to pay him to change his position; if the right and the baseline position are inconsistent, the actor will have to bear the costs of changing to conform with the right. A property rights assignment can be fixed by specific laws that insure legal protection of those rights; an implicit property rights assignment becomes evident through the policy-maker’s choice between subsidies and taxes.

At the second step, when the price and quantity of the product are
to be determined, the regulator can impose the socially optimal price and quantity; he can allow free trade in the market; or he can participate in the trade as a buyer, a seller, or a rule maker.

At the third step the Regulator can introduce either restrictions on existing mechanisms of exchange or new forms of those mechanisms. Table 3 below gives examples of possible policies that can influence each step of the transaction chain.

<table>
<thead>
<tr>
<th>Transaction steps</th>
<th>Property rights/ initial endowment assignment</th>
<th>Price/quantity determination</th>
<th>Optimal design of the mechanism of exchange</th>
</tr>
</thead>
<tbody>
<tr>
<td>Possible tools a policy-maker can choose at each step</td>
<td>Laws on property rights; legal protection of property rights; choice between taxes and subsidies, etc.</td>
<td>Tax, subsidies, Government as a buyer/seller, restrictions on trade, etc.</td>
<td>Restrictions on contracts, government as a contractor, mechanism provision (e.g., taxation, trading, etc.)</td>
</tr>
</tbody>
</table>

Table 1. Policy Instruments in the Transactions Chain Approach.
The last, fourth, step of an algorithm is a welfare analysis of GE effects of PE-optimal mechanisms.

It is important to understand that the regulation process is iterative – the market transaction is a continuous process, and changes in any step of this process can, and most probably will, affect other steps of the process. For example, it might be the case that optimal policy at the second step is conditional on optimal policy at the third step. If so, the Regulator has to fix the third step and then go back to the second. The process is complete when a stable solution is derived at each step of a transaction chain. Figure 5 illustrates how TCA is working.

Figure 5. Algorithm for the policy maker.

TCA does not offer something entirely original. All steps within “the chain” have been of interest to researchers for years. However it is important to connect the separate questions the policy maker faces,
understand how solution to one sub-problem will affect the other, and investigate how new policy changes circumstances in related markets; in other words to perform a complete analysis of the regulation problem. TCA helps to subdivide the complicated problem into smaller parts, and this makes it easier to find the solution, and at the same time to always remember the general picture and not be carried away by the important but small details of the problem. Sometimes it is enough to fix just one step of the transaction chain and let the market forces solve the rest of the problem. The fact that the process of policy design is iterative insures against attempts to solve the same problem twice at different steps of the transaction chain. Another advantage is that TCA gives the opportunity to determine how complication in the model at one step of the transaction will affect the whole picture, which helps to keep track of all consequences of new assumption of the model. Finally, it helps to combine the use of different tools of the economic analysis, from general market analysis to optimal contract theory and game theory, while moving from the aggregate market level of the problem to the individual level and back.
The next section illustrates how TCA works using as an example the nonpoint pollution from farms’ runoff problem.

Application: Use TCA to solve the nonpoint pollution problem.

The problem of nonpoint pollution from farms’ runoff can be formulated as follows.

There are \( n \) farmers in the watershed, who produce some kind of output and homogeneous pollution as a by-product. Farmers are assumed to be profit maximizers. Water consumers’ utility is decreasing in pollution. However, not only are farmers practically unaffected by the pollution produced by them, but also any reduction of pollution is costly for them. The problem the regulator faces is how to decrease the pollution level from the watershed to the socially optimal level \( A \).

Assume the following: farmers know the parameters of each others’ cost functions; and the regulator knows the realized distribution of those parameters, but he does not know which farmer has which parameters.
It is reasonable to assume that the “real world” cost function for abatement satisfies the following conditions:

1. \( C_i(0) = 0; \) It costs nothing not to produce abatement;

2. \( C_i(a_{\text{max}}) = \infty, \) where \( a_{\text{max}} \) is maximal possible abatement, which can be considered as a point of “zero pollution”. It is intuitive that any production process will always produce some, maybe very small level of pollution, and therefore the cost of abating the last unit of pollution is infinitely high;

3. if \( a_i > a_j \), then \( MC(a_i) > MC(a_j) \), it costs more to produce the next unit of abatement then the previous one.

In this model the cost of abatement function is approximated by a quadratic function, hence the cost of abatement function for the farmer \( i \) is

\[
C_i = \frac{1}{2} \alpha_i a_i^2 + \beta_i a_i
\]

where \( C_i \) - is the cost of abatement function for farmer \( i \);
\( \alpha_i, \beta_i \)- are the parameters describing farmer \( i \)'s cost of abatement function, and \( \alpha_i \)- rate of increase of marginal cost, and \( \beta_i \) –constant marginal cost;

\( a_i \) - is farmer \( i^{th} \)s level of abatement.

Given the form of the cost function, these assumptions can be rewritten as:

1. farmer \( i \) knows \( \alpha_i \) & \( \beta_j \) \( \forall j = 1, \ldots, n \);

2. the regulator knows the realized distribution of 
   \[ \{\alpha_i\}_{i=1,\ldots,n} \text{ & } \{\beta_i\}_{i=1,\ldots,n} \]

Below the TCA is used to solve the nonpoint source pollution from farms’ runoff problem.

**STEP 1. Property rights/initial endowment assignment**

First, the product of interest should be defined: call it clean water. Whoever owns it can do with it whatever he wants, pollute it or keep it clean.
The initial endowment will be assigned in terms of the proportion of clean water to polluted water. We choose that trading starts from the status quo for farmers. If the water-users want to reduce the level of the pollution, they have to buy clean water from farmers. Assume for now that the regulatory agency will act as a buyer on behalf of government, nonpoint polluters, or any other water-user. Therefore farmers will be subsidized to reduce pollution.

This manner of assigning the initial endowment seems to be reasonable in the initial stage of pollution regulation, since it does not use any punishment, and therefore does not create any incentives to hide the true level of pollution, or the fact that somebody is producing the pollution. On the contrary, polluting farmers will want to reveal themselves, since they can get extra profit from producing abatement. On the other hand, the Regulator does not need to know the exact number of people involved in the pollution process, which often is impossible to know. He is going to buy abatement from people who identify themselves as polluters.
This is not the only way to assign the initial endowment; however, once the choice was made, the next steps of policy design will consider instruments to be selected from the class of subsidies.

**STEP 2. Market trade: quantity and price determination.**

Let’s pick some level of abatement $A$ the regulator wants to achieve in the watershed. The regulator’s problem is to induce farmers to produce this level of abatement at minimum cost.

This problem was formalized as a Generalized Principal-Agent Problem and solved in Chapter 3. It was shown that the regulator’s optimal strategy is to announce that he will pay to a group of farmers according to rule: $A(\gamma A + \eta)$, and offer an algorithm for how the Association can distribute the total payment among its members. Then farmers who choose to accept the offer have to announce themselves.

The price for abatement is an upward-sloping linear function: $P = \gamma a + \eta$, where $a$ is a total abatement and $\gamma$ & $\eta$ are parameters the regulator chooses according to the rule given in Chapter 3. The price for abatement $A$ is $P^A = \gamma A + \eta$. The upward-sloping price line
creates additional incentives for farmers to stay in the Association, since payment per unit of abatement, and therefore total payment to each farmer increases with the number of farmers committing to the Association. Given this price structure, it is in best interests of every participant to act so nobody would want to leave the Association, but new members would want to join the group.

The total payment depends on the parameters chosen. Higher values of those parameters attract more farmers with higher abatement costs, lower values will restrict the number of participants to those with lower costs. So the regulator can control the number of the farmers in the Association. He should choose values of parameters $\gamma$ & $\eta$ that would minimize his cost. To be able to do it, the regulator needs to know which level of abatement the Association will produce for each value of parameters $\gamma$ & $\eta$. Farmers’ decisions on whether to produce abatement or not and how much, depend (in addition to parameters of the contract offered by the regulator) on the mechanism of exchange, i.e., how the regulator’s total payment for abatement is distributed within the Association. Given the design of the payment distribution inside the
Association, the regulator can choose the optimal number of participants – that number that will produce desirable level of abatement $A$ at lowest possible cost. That means that the regulator’s minimization problem is constrained by distribution rule(s) inside the Association.

In mathematical terms the regulator’s problem is:

$$\text{Min} \quad a(\gamma u + \eta)$$

st. \quad (1) \, \text{design of exchange} \quad \eta \neq 0 \quad a = A$$

Thus, Step 2 can be completed only when the mechanism of exchange is designed, which is a third step in TCA. In other words, a solution to the step 2 is conditioned on solution to the step 3.

**STEP 3. Optimal design of mechanism of exchange**

This problem is solved in Chapter 3. Therefore only short overview is given here.

Since the regulator can measure only the total level of abatement, if he pays the group of farmers who decide to participate, he does not face the hidden action problem. Farmers have to distribute this payment among
themselves. However, he should be concerned with farmers’ decisions to accept his offer. So it is his problem to create incentives for farmers to join the Association and to design the structure of the Association, so that farmers would believe that this type of contract works.

Given the upward-sloping contract curve, the sum of payments to two farmers, who produce abatement separately is less than the total payment those farmers will get if they form the Association. Thus, farmers who decided to join the Association have an incentive to stay in the Association and attract additional members.

Since the Association knows the parameters of each member cost function, it can calculate and assign to each member the optimal level of abatement $a_i^*$. However, the hidden action problem remains. It can be solved by designing a mechanism that is PE-efficient, individually rational, incentive compatible in dominant strategies, and budget balancing.

Individual rationality is necessary to insure that farmers will participate in the program, incentive compatibility in dominant strategies constraint is needed to guarantee that farmers who participate in the
program choose optimal level of abatement in both certainty and uncertainty cases, and budget balancing should hold, since only money that is received from the Regulator can be distributed among members of the Association.

If all those conditions hold, farmers will join the Association and produce the PE-optimal level of abatement under both certainty and uncertainty. However, since some administrative structure will have to be built there is a possibility for rent-seeking behavior by the Association’s administration. If that would happen, then farmers might decide to leave the Association. Therefore, the contract to be optimal should be able to correct the possible rent-seeking behavior inside the Association.

There are also some informational restrictions. Since the Association knows only the parameters of the cost functions, the total level of abatement, and the parameters of Regulator’s offer, the distribution rule can depend only on those variables.

It was shown in Chapter 3 that the contract of the following form is a solution to the problem:
\[ t_i = (\alpha, a^*_i + \beta_i) \left\{ \min \left[ a - \sum_{j \neq i} a_j^* \right] \right\} \frac{k-1}{k} \frac{k-2}{k} \frac{k-3}{k} \ldots \frac{\gamma^2}{k}; \]

With following notation:

- \( k_i \) - number of members in the Association
- \( t_i \) - \( i^{th} \) Farmer payment;
- \( a \) - The total level of pollution reduction;
- \( a_i \) - \( i^{th} \) Farmer level of pollution reduction;
- \( c_i \) - \( i^{th} \) Farmer cost of pollution reduction function;
- \( \alpha, \beta \) - Parameters of the cost of abatement function \( C_i(a_i) \);
- \( \pi_i \) - \( i^{th} \) Farmer profit function;
- \( \gamma, \eta \) - Parameters of “contract”.

And \( \{a_i^*\}_{i=1}^{k} \) is the solution of the system of equations:

\[ 2\times \gamma \times a + \eta = \alpha_i \times a_i + \beta_i \quad \forall i = 1, \ldots, k \]

Each farmer is assigned \( a_i^* \) - the level of abatement he has to produce in order for the outcome to be efficient. All \( a_i^* \) are calculated by the Association according to the following rule.
\[ \alpha_i a_i + \beta_i = 2 \gamma a + \eta, \text{ where } a = \sum_{i=1}^{k} a_i \text{ for all } i=1,\ldots. \] Each farmer chooses individually level of abatement \( a_i \) he is going to produce, and \( \sum_{i=1}^{k} a_i = a \).

The mechanism of exchange is therefore designed, and can be used to solve step 2.

**STEP 2 (continue). Determination of optimal parameters from regulator’s problem**

Once the regulator learns how the Association is going to respond to the contract he offers, he can set and solve his problem. From the solution to the Association problem the regulator understands that the parameters of the contract curve simultaneously determine the number of farmers in the Association and the level of abatement they are going to produce. Therefore, the regulator’s problem can be rewritten as following:

\[
\min_{\gamma, \eta} a(\gamma a + \eta)
\]

s.t. (1) participation constraint, \( k \) farmers in the Association
(2) Association’s response const., Association produces \( a \)
(3) \( a = A \)
The participation constraint insures that exactly \( k \) farmers decide to join the Association; the Association’s response constraint shows how much abatement those \( k \) farmers will produce.

The regulator’s goal is to achieve \( a = A \) at minimum cost. At the same time it does not matter to him how many members are in the Association. So he can choose, by setting parameters, optimal number of farmers in the Association, i.e., the number that will produce the required level of abatement at minimal cost to the regulator. As soon as the parameters of the contract curve are determined, the optimal price for the abatement is determined.

Using results from Chapter 3, we can write the regulator’s problem as the following:

\[
\begin{align*}
\text{Min} \quad & \gamma \eta (\gamma + \eta) \\
\text{s.t.} \quad & (1) \quad 2\gamma \alpha_k \left( \frac{\eta \lambda - \mu}{1 - 2\gamma \lambda} \right)^2 = k \left( 2\gamma \left( \frac{\eta \lambda - \mu}{1 - 2\gamma \lambda} \right) + \eta - \beta_k \right)^2 - \text{participation const.} \\
& (2) \quad a = \frac{\eta \lambda - \mu}{1 - 2\gamma \lambda} - \text{Association’s response const.} \\
& (3) \quad a = A
\end{align*}
\]

First, one needs to solve the constraints. The solution to this
system of equations is the optimal $\gamma^k$ & $\eta^k$ for each $k$-number of members in the Association. Therefore, $\gamma^k$ & $\eta^k$ can be considered as functions of $k$. Second, one has to substitute optimal $\gamma^k$ & $\eta^k$ into objective function and solve for the optimal number of members in the Association:

$$\text{Min} \quad A(\gamma^k A + \eta^k).$$

The solution to this part of the problem depends on the distribution of parameters of cost of abatement functions.

**STEP 4. Analysis of welfare effects of the designed policy on related markets**

The mechanism that is introduced above is designed so the regulator can buy from a watershed the level of abatement $A$ at minimum cost. Now it is necessary to find an optimal value of $A$ and evaluate the welfare effects of the policy on related markets.

An efficient policy is characterized by the following condition: marginal benefit to society from production of an extra unit of the product
is equal to marginal cost to society of production of this extra unit. Therefore, to design a PE-opt policy it is necessary to determine the marginal benefit and the marginal cost of production of an extra unit of abatement at some level A, and then find at which level A the marginal benefit is equal to the marginal cost in the market for environmental goods. In addition it is necessary to evaluate what are GE effects of the designed policy.

Farmers produce pollution as a by-product of production of good Q. The quantity of this good indirectly depends on the pollution level. Reduction of the pollution emitted will change the quantity of the good produced, so the product market will be affected. Therefore, the total social cost is the sum of the direct cost (money paid for abatement, which fully compensates the farmers) and the indirect costs (the welfare losses in related markets).

To estimate indirect cost of abatement it is necessary to perform a welfare analysis of an environmental policy on production markets. Spulber (1987) performed such an analysis for policies targeting point sources. The regulator can treat the Association as a point source polluter,
and thus he can incorporate the nonpoint sources (members of the Association) with other point source polluters into welfare analysis.

*Formal model.*

Let’s consider a competitive market for a good $Q$ that is supplied by $n$ nonpoint polluters. Each firm $j$ produces output $q^j$ and discharges effluents $e^j$. Market inverse demand is given by $P = P(Q)$, where $Q = \sum_{j=1}^{m} q^j$ is total output. External damages are $G(A)$, where $A$ is total level of abatement produced by the firms. Market inverse demand, $P$, is continuously differentiable, positive, and downward sloping. The damage cost function, $D$, is twice differentiable, positive, increasing and convex for $X > 0$.

A firm of type $j$ has a cost function

$$
C(q^j, e^j, \theta^j) = \frac{\sigma}{2} \left( (e^j)^2 + (q^j)^2 \right) - \xi e^j q^j - \theta^j e^j \quad \text{for } j = 1, \ldots, m
$$

(4.1)
Before any regulation was used there is equilibrium in the market with equilibrium price $P^e$, total equilibrium quantity $Q^e$, and individual equilibrium quantities $q^{je}$. The regulator knows all of them.

Since the market is competitive, then $P^e = MC^e = \sigma q^{je} - \xi e^{je}$. Therefore, regulator can calculate $e^{je}$.

Let $n < m$ polluters work in the same watershed.

And let the cost of abatement function (which is total lost profit due to abatement) be of the form $C^a(a) = \frac{1}{2} \alpha_i a_i^2 + \beta_i a_i$.

If the regulator contracts with the polluters in the watershed, then he can get abatement at the level $A$ for the cost of $A(\gamma A + \eta)$, where $\gamma$ & $\eta$ are functions of the distribution of the parameters of the cost of abatement functions $\{\alpha_i\}$ & $\{\beta_i\}, i = 1, ..., n$.

As a result of this policy, quantities of product supplied are reduced, so the equilibrium total quantity is reduced and the equilibrium price is increased.

The new price is equal to the new MC. It is possible to express MC as a function of abatement, therefore so and $P$. 

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\[ P = \sigma q^j - \xi (e^{j^k} - a_j) \] - individual supply functions;

\[ q^j = \frac{1}{\sigma} \left( P + \xi (e^{j^k} - a_j) \right) \] - individual quantity supplied;

\[ Q^A = \frac{1}{\sigma} \left( P k + \xi \left( \sum_{j=1}^{k} e^{j^k} - A \right) \right) \] - quantity, supplied by the Association;

\[ P = \frac{1}{k} \left( \sigma Q^A - \xi \sum_{j=1}^{k} e^{j^k} + \xi A \right) \] - supply from the Association.

Therefore we can consider product market with demand

\[ P(Q) = P\left( \sum_{j=k+1}^{m} q^j + Q^A \right) \], and supply functions:

\[ P = \sigma q^j - \xi e^j \] for

\[ j = k+1, \ldots, m \] and

\[ P = \frac{1}{k} \left( \sigma Q^A - \xi \sum_{j=1}^{k} e^{j^k} + \xi A \right) \].

Combining the demand and supply, we can solve for market equilibrium outputs:

\[
\begin{cases} 
q^j = q^j(e^{k+1},...,e^m,A) & \text{for } j = k+1,\ldots,m; \\
Q = Q(e^{k+1},...,e^m,A) & 
\end{cases}
\]

We can calculate effects of effluents and A (the level of abatement that the regulator bought from the Association):
\[
\begin{align*}
P' \left( \sum_{j=k+1}^{m} q^j + Q^A \right) \left( \sum \frac{\partial q^j}{\partial A} + \frac{\partial Q}{\partial A} \right) &= \sigma \frac{\partial q^j}{\partial A} \quad \text{for } j = k + 1, \ldots, m \\
P' \left( \sum_{j=k+1}^{m} q^j + Q^A \right) \left( \sum \frac{\partial q^j}{\partial A} + \frac{\partial Q}{\partial A} \right) &= \frac{\sigma Q^A}{k} + \frac{\xi}{k} 
\end{align*}
\]

We can also conclude, that a firm’s market equilibrium output is increasing in the \( A \), but output, produced by the Association is decreasing in \( A \). Equilibrium price has increased due to abatement, and equilibrium quantity has decreased in pollution.

**Effect of the policy on Social Welfare**

The change in the social welfare is equal to sum of the change of the Consumer Surplus \( \Delta CS \), change in Producer Surplus \( \Delta PS \), and environmental gain.

Denote new equilibrium price as \( P(e^{k+1}, \ldots, e^m, A) \), and new equilibrium output as \( Q(P(e^{k+1}, \ldots, e^m, A)) \).

Consumer surplus then will decrease by

\[
\Delta CS = \int_{P'} Q' \left( P(e^{k+1}, \ldots, e^m, A) \right)
\]
Producer surplus will increase, since members of the Association are compensated for any loss in profit, and all others enjoy increase in both price and quantity by $\Delta PS$.

Therefore, total (direct and indirect) cost of abatement to society is $\Delta CS(A) + A(\gamma A + \eta)$, and total (direct and indirect) benefit to society is $G(A) + \Delta PS$.

If $\Delta PS(A) - \Delta CS(A)$ is non-trivial, then a policy that was designed in steps 1-3 is not GE-optimal. In this case a policy maker needs either to accept a sub-optimal outcome and bear some losses, or to go back to step 1 of the algorithm and work on design of a policy that regulates two markets simultaneously. Technically it is much more complicated problem and might require a mechanism that is more sophisticated then the one developed in Chapter 3 of the dissertation. Sub-optimal $A^*$ can be found from the system:

$$
\left(Q(P(e^{k+1},...,e^m,A)) - Q^A\right) \times \frac{\partial P(e^{k+1},...,e^m,A)}{\partial A} + G'(A) = \\
= Q(P(e^{k+1},...,e^m,A)) \times \frac{\partial P(e^{k+1},...,e^m,A)}{\partial A} + 2\gamma A + \eta
$$
The regulator should implement the policy, if

\[ G(A^*) - \Delta CS(A^*) + \Delta PS - A^* (\gamma A^* + \eta) \geq 0. \]

However, if a product market is large and open to international trade (as is usually true in the case of grain or corn production), then equilibrium price would not change and neither consumers’ nor producers’ surpluses in the production market would change. Product markets in this case are unaffected, and the PE-optimal policy is also GE-optimal. Thus the optimal level of abatement \( A^* \) can be found from equation:

\[ G'(A) = 2\gamma A + \eta. \]

The regulator should implement the policy, if

\[ G(A^*) - A^* (\gamma A^* + \eta) \geq 0. \]

**STEP 2 (completion). Determination of optimal quantity and price.**

Finally, the Second Step in TCA (quantity/price determination) can be completed. The optimal quantity (a first-best or second-best optimum, depending on results from step 4) of abatement is \( A^* \), and optimal price for this amount is \( \gamma A^* + \eta \), \( A^* \) is determined in step 4. Therefore, in this case the solution to Step 2 was conditioned on solutions to step 3 and step 4.
Summary

In this Chapter the Transaction Chain Approach (TCA) to policy design has been presented and applied to the nonpoint pollution regulation problem. I demonstrated how to use TCA to design a regulatory policy that achieves a PE-optimal outcome (or a GE-optimal outcome if product markets are large and open).

The idea behind this approach is to consider three steps of market transaction – property rights/initial endowment assignment, price and quantity determination, and money/product exchange sequentially, choose a regulatory intervention that is optimal for each step of the transaction, and then combine all those interventions into the whole policy.

TCA requires that each proposed policy be evaluated by welfare analysis of the effects of the policy on targeted and related markets. This helps to account for all effects of a regulatory policy and alert the policy-maker in cases where a policy that has a positive effect on one market would have a large negative effect on other markets. Furthermore, it helps
to derive restrictions on implementation of policy, to limit potential negative effects in related markets.

TCA does not offer something entirely original. However it simplifies the policy analysis by subdividing a complicated problem into smaller parts, which makes it easier to find the solution. At the same time it helps the analyst to keep track of the general picture and avoid being carried away with important but small details of the problem. Sometimes it is enough to apply a policy to one step of the transaction chain and let the market solve the rest of the problem.

Another advantage is that TCA provides the opportunity to watch how complication in the model for one step of the transaction will affect the whole picture, which helps to keep track of all consequences of new assumptions of the model.

Finally, it provides a coherent framework within which to combine the use of different tools of economic analysis, from general market analysis to optimal contract theory and game theory, while moving from the aggregate market level of the problem to the individual level and back.
The solution to the nonpoint pollution regulation problem that was derived using TCA is for the regulator to buy pollution abatement from farmers using the contract that was described in the Chapter 3. Specifically, the regulator pays for the total performance of the Association of farmers and delegates the distribution function to the members of the group.

A welfare analysis of effects of a policy on both environmental and production markets has shown what is PE-optimal level of abatement that the regulator should buy from the Association. This analysis also has shown that the PE-optimal policy that was derived is not necessarily optimal in GE sense, but large-markets and open-markets conditions are likely to minimize the GE problems in this application of mechanism design to the NPS problem.

It is important to recognize that although the policy-maker’s informational requirements with this policy are lower than with other policies for regulating nonpoint source pollution, they are still quite high. In particular, the regulator needs to know the distribution of parameters of the farmers’ cost functions, and polluters need to know their own and each
other’s costs of abatement functions. A possible way to extend a model is to consider it in a dynamic setting to see whether a regulator and farmers can learn over time about costs of abatement in a watershed, and therefore informational requirements can be reduced.
CHAPTER 5

SUMMARY AND RESULTS

The purpose of this study was to design a regulatory policy to solve a nonpoint source water pollution problem. Our research resulted in contributions in three areas of economic theory: policy design, theory of incentives (the generalized principal agent problem), and environmental economics (the nonpoint source water pollution problem).

Policy Design

The Transaction Chain Approach (TCA) was used in this study to solve the nonpoint pollution problem. This approach can be considered as a way to reformulate the problem so it will look clearer for the Regulator, and enable the Regulator to determine how to solve the problem.
The idea behind this approach is to consider a market transaction in three steps – property rights/initial endowment assignment, price and quantity determination, and money/product exchange -- sequentially, choose a regulatory intervention that is optimal for each step of the transaction, and then combine all those interventions into the whole policy. TCA then requires that each proposed policy be evaluated by welfare analysis of the effects of the policy on targeted and related markets. This helps to account for all effects of a regulatory policy and alert the policy-maker in cases where a policy that has a positive effect on one market would have a large negative effect on other markets. Furthermore, it helps to derive restrictions on implementation of policy, to limit potential negative effects in related markets.

TCA does not offer something entirely original. However it simplifies the policy analysis by subdividing a complicated problem into smaller parts, which makes it easier to find the solution. At the same time it helps the analyst to keep track of the general picture and avoid being carried away with important but small details of the problem. Sometimes it
is enough to apply a policy to one step of the transaction chain and let the market solve the rest of the problem.

*Generalized Principal-Agent problem*

In this study a special case of the generalized principal-agent problem was considered. Given the following restrictions:

1. principal knows the distribution of agents’ types,
2. agents know types of each other,
3. principal and agents know total level of production, and
4. utility functions are quasi-linear (risk neutrality),

I have shown that, under assumptions consistent with the NPS pollution problem, it is possible to decompose the bivariate optimization problem (maximization of principal’s utility with respect to type and action) into two univariate variational problems in the multiagents case, and design a two-step contract that solves both the asymmetric information and hidden action problems. This extends the result of Faynzilberg and Kumar (2000), who have shown that under some specific
conditions, and in the case with one agent, the generalized principal-agent problem can be decomposed into two univariate variational problems (maximization of principal’s utility with respect to type and maximization of principal’s utility with respect to action).

It was possible to separate the adverse selection and moral hazard problems because (1) the total level of abatement can be observed, and (2) the agents know each other’s types. Therefore the principal can offer a single payment for the total abatement to the group of farmers, and delegate the distribution problem to the Association (which does not face an adverse selection problem). The principal’s only problem is to design a contract that will attract the lowest-cost abaters to join the Association. Once formed, the Association has to take care only of the moral hazard problem.

The adverse selection problem is solved by specifying a contract in which the price paid per unit of abatement is increasing in abatement. The payment schedule is designed so it creates additional interdependence among agents so their performance would be correlated (to employ results of Mookherjee (1984), Nalebuff and Stiglitz (1983), and Green and
Stockey (1983)), and it attracts farmers with lowest cost of abatement to the group.

The responsibility for distributing the payment and encouraging agents to deliver performance is vested in the group of agents (called the Association), an arrangement that utilizes the informational advantages that agents enjoy. To distribute the money among members of the Association a contract is designed that solves a moral hazard problem and has several nice properties. One of them is that the mechanism is designed to be incentive compatible in dominant strategies, therefore it works equally efficiently under both certainty and uncertainty. Another useful property of the mechanism proposed here is that it is budget-balancing. This property gives the mechanism an advantage over Groves mechanisms since no member of the Groves mechanisms satisfies a budget balancing condition. Although Green and Laffont (1977) have shown that Groves transfers are the only transfers that make truthful revelation a dominant strategy if no restrictions are imposed on the domain of agents’ types, it is demonstrated here that under restrictions on the domain of agents’ types imposed in the model (agents’ types are singleton), it is possible to design
a dominant strategy mechanism, which is not Groves, to resolve the moral hazard problem.

This work demonstrates that agents willing to accept joint responsibility for performance (i.e., to join the Association), would enjoy profit from producing abatement jointly with agricultural commodities.

**Nonpoint Source Water Pollution Regulation**

I have demonstrated that the nonpoint pollution problem can be solved by designing a performance-based contract that creates incentives for nonpoint polluters to adopt abatement technologies and reduce the level of pollution to a socially optimal level.

Despite the fact that the nonpoint source pollution problem is characterized by existence of both types of asymmetric information, the existing NPS literature solves the adverse selection and moral hazard problems only separately. The adverse selection problem has been investigated by Spulber (1989), Dosi and Moretto (1990), Shortle and Dunn (1986), and others. Moral hazard was addressed by Segerson (1988),
Dosi and Moretto (1990, 1992), Xepapadeas (1991, 1992), others. However, policies designed in those studies cannot be efficiently used in NPS regulation, since they omit such important feature of the problem as existence of both moral hazard and adverse selection simultaneously.

I have demonstrated that combination of two types of asymmetric information (adverse selection and moral hazard) can be solved through decentralization, by using the informational advantage of farmers (assuming that farmers have more information about each other than the regulator does).

The solution to this problem calls for the regulator to contract for abatement to be produced by a group of farmers, paying for the total abatement performance achieved by the group. The responsibility for distributing the payment and encouraging farmers to deliver abatement performance is vested in the group of farmers (called the Association), an arrangement that utilizes the informational advantages that farmers in the same watershed enjoy.

If one substitutes for the Regulator a (group of) point source polluter(s) seeking to purchase pollution reduction credits from the group
of farmers, the mechanism would work in the same way. Thus, I have designed a mechanism adaptable to performance-based regulation of NPS pollution and performance-based point-nonpoint pollution permit trading. Performance-based mechanisms for pollution control have well-recognized advantages – responsibility for pollution reduction is assigned to low-cost abaters within the group, while individual polluters are free to choose cost-minimizing abatement technologies and to take advantage of cost-reducing innovations in pollution control – but existing policies addressed to NPS pollution have foregone these advantages by conceding (prematurely, we would argue) the impracticality of performance-based instruments for NPS. This work demonstrates that this concession is no longer necessary – NPS polluters willing to accept joint responsibility for performance (i.e., to join the Association), would enjoy cost-savings in compliance with regulations, or increased profits from abatement (whether purchased by the Regulator or by point-source polluters seeking pollution reduction credits), as the case may be.

I emphasize that the contract inside the Association is relatively straightforward in application (certainly not as confusing as the farm
programs and tax laws that farmers ordinarily deal with). It may require some relatively forbidding mathematics to demonstrate the properties of our mechanism, but not to implement it in practice.

This problem was considered here in, and the mechanism was designed for, a static setting. In order to achieve an efficient allocation, the Regulator needs to know the distribution of the parameters of the abatement cost functions for farmers in the watershed. While one could expect the Regulator to have some information (perhaps good information) about these parameters, it is unlikely he would have knowledge as complete as is assumed here. A challenge for future research is to examine the possibility that, in a dynamic setting, the Regulator might be able to learn the distribution of the parameters of the farmers’ abatement cost functions.
APPENDIX A

PROOF THAT THE MECHANISM IS INDIVIDUALLY RATIONAL (IR), INCENTIVE-COMPATIBLE IN DOMINANT STRATEGIES (DIC) AND BUDGET BALANCING (BB)
Individual rationality (IR) - Farmers will decide to accept the contract only if they will be at least as well off as without contract;

To show that this condition holds we need to show that \( \pi_i(a_i^*) \geq 0 \) \( \forall i. \)

\[
\pi_i(a_i^*) = (\alpha_i a_i^* + \beta_i) \left( \min \left\{ a^* - \sum_{j \neq i} a_j^* ; 2a^* - a^* - \sum_{j \neq i} a_j^* \right\} \right) - \frac{\gamma a_i^*}{k} - \frac{1}{2} \alpha_i a_i^{*2} - \beta_i a_i^* =
\]

\[
= (\alpha_i a_i^* + \beta_i) a_i^* - \frac{\gamma a_i^{*2}}{k} - \frac{1}{2} \alpha_i a_i^{*2} - \beta_i a_i^* = \frac{1}{2} \alpha_i a_i^{*2} - \gamma a_i^{*2}
\]

\[
= \left\{ \text{But it is known that} \frac{1}{2} \alpha_k a_k^{*2} = \frac{\gamma a_k^{*2}}{k} \right\} =
\]

\[
= \frac{1}{2} \alpha_i a_i^{*2} - \frac{1}{2} \alpha_k a_k^{*2} = \frac{1}{2} (\alpha_i a_i^{*2} - \alpha_k a_k^{*2})
\]

Substitute condition \( a_i = \frac{2\gamma \alpha + \eta - \beta_i}{\alpha_i} \), \( \forall i \) into the above expression:

\[
\frac{1}{2} (\alpha_i a_i^{*2} - \alpha_k a_k^{*2}) = \frac{1}{2} \left( \frac{(2\gamma \alpha + \eta - \beta_i)^2}{\alpha_i} - \frac{(2\gamma \alpha + \eta - \beta_k)^2}{\alpha_k} \right).
\]

Since \( \beta_i \leq \beta_k \), \( \forall i \) than

\[
(2\gamma \alpha + \eta - \beta_i)^2 \geq (2\gamma \alpha + \eta - \beta_k)^2,
\]

and since \( \alpha_i \leq \alpha_k \), \( \forall i \) than

\[
\frac{(2\gamma \alpha + \eta - \beta_i)^2}{\alpha_i} \geq \frac{(2\gamma \alpha + \eta - \beta_k)^2}{\alpha_k}.
\]

That means that \( \frac{1}{2} \left( \frac{(2\gamma \alpha + \eta - \beta_i)^2}{\alpha_i} - \frac{(2\gamma \alpha + \eta - \beta_k)^2}{\alpha_k} \right) \geq 0 \), \( \forall i. \)
Therefore, \( \pi_i(a_i^*) \geq 0 \). So participation constraint (IR) is satisfied.

**Incentive compatibility constraints**

\[(\text{DIC}) \ u_i(y(\theta_i, \theta_{-i}), \theta_i) \geq u_i(y(\hat{\theta}_i, \theta_{-i})\theta_i) ; \]

if \( \Delta < 0 \), then

\[
u_i(y(\theta_i, \theta_{-i}), \theta_i) - u_i(y(\hat{\theta}_i, \theta_{-i})\theta = (t_i^* - C_i^*) - (t_i(\Delta) - C_i(\Delta)) =
\]

\[
= \left( \alpha a_i^* + \beta_i \right) (a_i^*) - \frac{\gamma a_i^*}{k} - \left( \frac{1}{2} \alpha a_i^* + \beta_i a_i^* \right) - \left( \alpha a_i^* + \beta_i \right) (a_i^* - |\Delta|) - \frac{\gamma a_i^*}{k} - \left( \frac{1}{2} \alpha (a_i^* - \Delta_i)^2 + \beta_i (a_i^* - |\Delta|) \right) =
\]

\[
= \alpha a_i^* \Delta_i - \left( \frac{1}{2} \alpha (a_i^* - \Delta_i)^2 + 2a_i^* |\Delta| - |\Delta|^2 \right) =
\]

\[
= \alpha a_i^* |\Delta| - \alpha a_i^* |\Delta| + \frac{1}{2} \alpha |\Delta|^2 = \frac{1}{2} \alpha |\Delta|^2 \geq 0 \implies
\]

\[
\implies u_i(y(\theta_i, \theta_{-i}), \theta_i) \geq u_i(y(\hat{\theta}_i, \theta_{-i})\theta
\]

if \( \Delta > 0 \), then
\[ u_i(y(\theta_i, \theta_{-i}), \theta_i) - u_i(y(\bar{\theta}_i, \theta_{-i}), \theta_i) = \left( t^*_i - C^*_i \right) - \left( t_i(\Delta_i) - C_i(\Delta_i) \right) = \]

\[= \left( (\alpha_i a_i^* + \beta_i) (a_i^*) - \frac{\gamma a_i^{*2}}{k} - \left( \frac{1}{2} \alpha_i a_i^{*2} + \beta_i a_i^* \right) \right) - \left( (\alpha_i a_i^* + \beta_i) (a_i^* + \Delta_i) - \frac{\gamma a_i^{*2}}{k} - \left( \frac{1}{2} \alpha_i (a_i^* + \Delta_i)^2 + \beta_i (a_i^* + \Delta_i) \right) \right) = \]

\[= - (\alpha_i a_i^* + \beta_i) \Delta_i - \frac{1}{2} \alpha_i \left( a_i^{*2} - (a_i^* + |\Delta|)^2 \right) - \beta_i |\Delta| \]

\[= - \alpha_i a_i^* \Delta_i - \frac{1}{2} \alpha_i \left( a_i^{*2} - a_i^{*2} - 2a_i^* \Delta_i - \Delta_i^2 \right) = \]

\[= \alpha_i a_i^* \Delta_i - \alpha_i a_i^* \Delta_i + \frac{1}{2} \alpha_i \Delta_i^2 = \frac{1}{2} \alpha_i \Delta_i^2 \geq 0 \Rightarrow \]

\[\Rightarrow u_i(y(\theta_i, \theta_{-i}), \theta_i) \geq u_i(y(\bar{\theta}_i, \theta_{-i}), \theta_i) \]

Therefore, Incentive compatibility constraint is satisfied in dominant strategies.

**Budget balancing constraint** - Sum of money transfers to individual farmers cannot be greater then money payment, received by the Association.

Each farmer receives the payment from the Association:

\[ t_i = (\alpha_i a_i^* + \beta_i) \left( \text{Min} \left\{ a - \sum_{j \neq i} a_j^*; 2a_i^* - a - \sum_{j \neq i} a_j^* \right\} \right) - \frac{\gamma a_i^{*2}}{k}. \]

Total payment from the Regulator should be not less then sum of money transfers to individual farmers:
\[ \sum_{i} t_i \leq a(\gamma a + \eta) \]

\[ \sum_{i} t_i = \sum_{i} \left( (\alpha, a_i^* + \beta, \min \left\{ a - \sum_{j \neq i} a_j^*; 2a^* - a - \sum_{j \neq i} a_j^* \right\} - \frac{\gamma a^*}{k} \right) = \]

\[ \{ \text{it is true } \forall i \alpha, a_i^* + \beta = 2\gamma a^* + \eta \} = \]

\[ \sum_{i} \left( (2\gamma a^* + \eta) \min \left\{ a - \sum_{j \neq i} a_j^*; 2a^* - a - \sum_{j \neq i} a_j^* \right\} - \gamma a^* \right) = \]

\[ = (2\gamma a^* + \eta) \sum_{i} \left( \min \left\{ \sum_{i} (a_i^* + \Delta_i) - \sum_{j \neq i} a_j^*; 2a^* - \sum_{i} (a_i^* + \Delta_i) - \sum_{j \neq i} a_j^* \right\} - \gamma a^* \right) = \]

\[ = (2\gamma a^* + \eta) \sum_{i} \left( \min \left\{ a_i^* + \sum_{i} (\Delta_i); a_i^* - \sum_{i} (\Delta_i) \right\} - \gamma a^* \right) = \]

\[ \begin{cases} \text{if } \sum_{i} (\Delta_i) < 0, \text{ then } \min \left\{ a_i^* + \sum_{i} (\Delta_i); a_i^* - \sum_{i} (\Delta_i) \right\} = a_i^* + \sum_{i} (\Delta_i) \\ \text{if } \sum_{i} (\Delta_i) > 0, \text{ then } \min \left\{ a_i^* + \sum_{i} (\Delta_i); a_i^* - \sum_{i} (\Delta_i) \right\} = a_i^* - \sum_{i} (\Delta_i) \end{cases} \]

therefore it can be written as

\[ \min \left\{ a_i^* + \sum_{i} (\Delta_i); a_i^* - \sum_{i} (\Delta_i) \right\} = a_i^* - \sum_{i} (\Delta_i) \]
Now we need to compare two expressions:

\[
\left( a^* + \sum_i (\Delta_i) \right) \left( \gamma \left( a^* + \sum_i (\Delta_i) \right) + \eta \right) = a^* (\gamma a^* + \eta) + (2\gamma a^* + \eta) \gamma \left( \sum_i (\Delta_i) \right)^2
\]

On the other hand \( a(\gamma a + \eta) = \left( a^* + \sum_i (\Delta_i) \right) \left( \gamma a^* + \sum_i (\Delta_i) \right) + \eta \)

\[
= a^* (\gamma a^* + \eta) + (2\gamma a^* + \eta) \gamma \left( \sum_i (\Delta_i) \right)^2
\]

It is the same as to compare the following two expressions:
\[-(2\gamma \alpha^* + \eta) \left| \sum_i (\Delta_i) \right| \quad \text{and} \quad (2\gamma \alpha^* + \eta) \sum_i (\Delta_i) + \gamma \left( \sum_i (\Delta_i) \right)^2,\]

if \( \sum_i (\Delta_i) \geq 0, \) then

\[-(2\gamma \alpha^* + \eta) \sum_i (\Delta_i) \leq (2\gamma \alpha^* + \eta) \sum_i (\Delta_i) + \gamma \left( \sum_i (\Delta_i) \right)^2,\]

and therefore \( \sum_i t_i \leq a(\gamma \alpha + \eta); \)

if \( \sum_i (\Delta_i) \leq 0, \) then

\[-(2\gamma \alpha^* + \eta) \left| \sum_i (\Delta_i) \right| \quad \text{and} \quad -(2\gamma \alpha^* + \eta) \sum_i (\Delta_i) + \gamma \left( \sum_i (\Delta_i) \right)^2 \iff \]

\[-(2\gamma \alpha^* + \eta) \sum_i (\Delta_i) (k - 1) \leq \gamma \left( \sum_i (\Delta_i) \right)^2;\]

and therefore \( \sum_i t_i \leq a(\gamma \alpha + \eta). \)

Therefore budget-balancing constraint is satisfied.
APPENDIX B

RESTRICTIONS ON PARAMETERS OF THE REGULATOR’S OFFER
From appendix C it is known that
\[ a = \frac{\eta \lambda_k - \mu_k}{1 - 2\gamma \lambda_k} > 0 \]
\[ \eta \lambda_j - \mu_j = \eta \sum_{i=1}^{k} \frac{1}{\alpha_i} - \sum_{i=1}^{k} \frac{\beta_i}{\alpha_i} = \sum_{i=1}^{k} \frac{\eta - \beta_i}{\alpha_i} \]
\[ 1 - 2\gamma \lambda_k = 1 - 2\gamma \sum_{i=1}^{k} \frac{1}{\alpha_i} = 1 - \sum_{i=1}^{k} \frac{2\gamma}{\alpha_i} \]

If there is only one member in the Association, then
\[ a = \frac{\eta - \beta_1}{\alpha_1} = \frac{\eta - \beta_1}{\alpha_1 - 2\gamma} > 0 \]
\[ \Rightarrow \begin{cases} \eta - \beta_1 > 0 & \text{(case 1)} \\ \alpha_1 - 2\gamma > 0 & \text{(case 2)} \end{cases} \]

If the case 2 is true, then farmers will choose to produce infinite amount of abatement for infinitely high cost.

If the Regulator wants to induce some specific level of abatement, then he needs to choose case 1. Since
\[ \alpha_1 < \alpha_2 < \ldots < \alpha_k \quad \text{and} \quad \alpha_1 > 2\gamma, \]
then \( \forall i : \alpha_i > 2\gamma. \)
APPENDIX C

RELATIONSHIP BETWEEN PARAMETERS OF THE REGULATOR’S OFFER AND THE NUMBER OF MEMBERS OF THE ASSOCIATION
The Regulator’s problem:

\[
\min_{\gamma, \eta} a(\gamma a + \eta)
\]

s.t. (1) \(2\gamma k \left( \frac{\eta \lambda - \mu}{1 - 2\gamma \lambda} \right)^2 = k(2\gamma \left( \frac{\eta \lambda - \mu}{1 - 2\gamma \lambda} \right) + \eta - \beta_i)^2 - \text{participation const.}\)

(2) \(a = \frac{\eta \lambda - \mu}{1 - 2\gamma \lambda} - \text{Association’s response const.}\)

(3) \(a = A\)

First, we need to solve constraints with respect to \(\gamma \& \eta\):
\[
\begin{aligned}
& 2\gamma\alpha_i \left( \frac{\eta\lambda - \mu}{1 - 2\gamma\lambda} \right)^2 = k \left[ 2\gamma \left( \frac{\eta\lambda - \mu}{1 - 2\gamma\lambda} \right) + \eta - \beta_k \right]^2 \\
& a = \frac{\eta\lambda - \mu}{1 - 2\gamma\lambda} \\
& a = A \\
& \Rightarrow \\
& 2\gamma\alpha_i A^2 = k \left( 2\gamma A + \eta - \beta_k \right)^2 \\
& \eta = \frac{A(1 - 2\gamma\lambda) + \mu}{\lambda} \\
& \Rightarrow \\
& 2\gamma\alpha_i A^2 = k \left( 2\gamma A + \frac{A(1 - 2\gamma\lambda) + \mu}{\lambda} - \beta_k \right)^2 \\
& \eta = \frac{A(1 - 2\gamma\lambda) + \mu}{\lambda} \\
& \Rightarrow \\
& \gamma = \frac{k(A - \beta_k \lambda + \mu)^2}{2A^2\alpha_i \lambda^2} \\
& \eta = \frac{A(1 - 2\gamma\lambda) + \mu}{\lambda} \\
& \Rightarrow \\
& \gamma = \frac{k(A - \beta_k \lambda + \mu)^2}{2A^2\alpha_i \lambda^2} \\
& \eta = \frac{1}{\lambda} \left[ \mu + A \left( 1 - \frac{k(\lambda - \beta_k \lambda + \mu)^2}{A^2\alpha_i \lambda} \right) \right]
\end{aligned}
\]
Therefore, if the Regulator wants to have $k$ farmers in the Association, then he needs to set

$$\gamma^k = \frac{k(A - \beta_k \lambda + \mu)^2}{2A^2 \alpha_k \lambda^2}$$

and

$$\eta^k = \frac{1}{\lambda} \left[ \mu + A \left( 1 - \frac{k(A - \beta_k \lambda + \mu)^2}{A^2 \alpha_k \lambda} \right) \right].$$
Bibliography


Crémer, J., and McLean, R., 1985; “Optimal selling strategies under uncertainty for a discriminating monopolist when demands are interdependent.” *Econometrica* 53: 345-361


Green, J. and Stockey, N., 1983; “A Comparison of Tournaments and Contracts”, *Journal-of-Political-Economy* 91(3): 349-64


McAfee, P., J. McMillan, and P. Reny, 1989; “Extracting the surplus in the common-value auction.” Mimeo, University of Western Ontario

Maskin, E., and Riley, J., 1980; “Auction design with correlated values.” Mimeo, University of California, Los Angeles


1986 reauthorization of the Clean Water Act, Section 319

Clean Air Act Amendments of 1990, Title IV