ABSTRACT

Title of Dissertation: THE ROLE OF INFORMATION IN POLICY IMPLEMENTATION

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Firms will comply with a regulation when the expected costs of noncompliance exceed the expected benefits. If the regulator has incomplete enforcement information and firms are aware of this, it will enter into their calculation of expected benefits and costs. The literature on regulatory enforcement typically assumes that the regulator is able to identify the universe of regulated firms. In my dissertation, I relax this assumption by allowing for the existence of regulatory information gaps and examine the implications for compliance and ambient environmental quality.

The first chapter reviews the literature on the enforcement of environmental regulations. The second chapter examines the effect of regulatory information gaps on a firm's compliance strategy. The theoretical results indicate that a firm with a sufficiently low probability of being subject to enforcement action will delay compliance. This prediction is tested empirically in the context of nutrient management regulations in Maryland. The econometric results indicate that the probability of being included in the MDA farm registry is associated with a statistically significant increase in the probability of being in compliance with nutrient management regulations.

If information gaps have an effect on a firm's compliance decision, then they may potentially have consequent effects on ambient environmental quality. In the third chapter, I develop a theoretical model of the firm's optimal level of emissions under information gaps. The theoretical results indicate that the optimal level of emissions is decreasing in the likelihood of being known to the regulator. If decreases in a firm's emissions result in decreases in ambient pollution levels, then ambient pollution levels are also decreasing in the probability of being known. I test this prediction empirically within the context of Clean Water Act (CWA) permit regulations. The empirical results indicate that a one percentage point increase in the share of firms known to the regulator results in a 0.43% - 0.49% percent decrease in ambient pollutant concentration for three out of the four pollutants. Increasing the share of known firms by 5 percentage points could lead to benefits, in terms of improved water quality, of $165.9 million per year.

THE ROLE OF INFORMATION IN POLICY IMPLEMENTATION

by

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Dedication

To my wonderful parents, Hirut Desta and Tesfaye Wondim, for their encouragement, kind words, sacrifices, and unparalleled support. You both mean the world to me and I could not have done it without you two.

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1 Introduction

The primary goal of environmental regulations is to improve environmental quality. The extent to which this goal is achieved depends on several factors, one of which is the effectiveness of regulatory enforcement. Effective enforcement strategies must provide strong enough incentives to induce firms to comply with the regulation. Economic theory suggests that firms will comply with a regulation only if the expected net benefits of compliance exceed the expected net benefits of noncompliance (Becker 1968). Regulators may alter firms' compliance incentives through the use of enforcement instruments such as self-reporting, inspections, warnings, fines, and criminal sanctions.

The literature on the enforcement of environmental regulations examines the optimal enforcement policy in various enforcement settings including instances where information is incomplete. These include scenarios in which the monitoring probability is less than one so that the regulator observes the compliance status of a subset of firms, when monitoring technologies are imperfect and detect compliance status with error, and when there exist information asymmetries about compliance costs. One aspect that the literature does not consider is incomplete information about the universe of firms subject to regulation. Obtaining a complete census of the universe may be difficult for two reasons: (1) it may be difficult to initially obtain information on the identities of the relevant agents, particularly if the regulated universe is vast and (2) it may be difficult to maintain up-to-date information over time, particularly if turnover is high. As a result, the regulator may partially rely on self-identification to obtain information on the universe of regulated firms; when firms apply for any required permits to pollute, they are essentially identifying themselves as belonging to the regulated universe. However, firms have an incentive to remain unknown to the regulator because if they are unknown, then they will not be subject to monitoring and enforcement and incur the associated costs. In my dissertation, I relax this assumption by allowing for the existence of regulatory information gaps and examine the implications for compliance and ambient environmental quality.

Chapter 2 reviews the economics literature on the enforcement of environmental regulations. Chapter 3 examines the effect of incomplete enforcement information on farm compliance with nutrient management regulations in Maryland. The results indicate that an increase the share of farms known to the regulator results in a significant decrease in the likelihood of compliance. If incomplete enforcement information has a negative effect on compliance, then it may also have consequent effects on ambient environmental conditions. Chapter 4 examines the effect of incomplete enforcement information on ambient water quality within the context of Clean Water Act permit regulations in the Mississippi River Basin. The results indicate that an increase in the share of facilities known to the regulator results in a significant decrease in ambient pollutant concentration for three of the four pollutants modeled. Thus, incomplete enforcement information has implications for both compliance and ambient environmental quality.

2 A Review of the Literature on the Economics of the Enforcement of Environmental Regulations

2.1 Introduction

Prior to the 1960s, environmental law in the United States was largely decentralized with the federal government having little authority. In the late 1960s, growing public concern over environmental quality led to a push for federal environmental legislation and regulation. Around this time, the Environmental Protection Agency was established to research pollutants, monitor ambient environmental conditions, establish environmental baselines, set standards for both individual pollutants as well as air and water quality, and monitor and enforce those standards. Additionally, over the next two decades, several federal environmental laws were passed such as the Clean Air Act (CAA), the Clean Water Act (CWA), and the Resource Conservation and Recovery Act (RCRA), to name a few.

The goal of these laws is to improve or preserve environmental quality and protect human health. The extent to which environmental laws and regulations achieve their goals depends, at least in part, on the extent to which firms within the regulatory purview comply with the laws and regulations. Standard economic theory finds that a rational, risk-neutral firm will violate a law or regulation if the expected benefits of noncompliance exceed the expected costs (Becker 1968). The expected benefits of noncompliance include avoiding compliance costs. Compliance costs include any costs associated with adopting required technology, hiring consultants, administrative fees, etc. Firms may also incur costs that arise from changes in the production process as a result of compliance.

A rational, risk-neutral firm will compare these expected benefits of noncompliance with the expected costs. The costs of noncompliance include any legal penalties that may be imposed, costs arising from more stringent enforcement in the future, operational strains from having poor relationships with regulatory agencies, and costs arising from tarnished public reputation. However, a firm will incur these costs only if a violation is detected and punishment is pursued through either public or private monitoring and enforcement of the law. Therefore, a firm will base its compliance decision on its expectations of the costs.

A regulator may alter a firm's compliance incentives through enforcement. Effective enforcement strategies provide strong enough incentives in order to induce compliance. Instruments such as inspections, self-reporting, audits, warnings, fines, and criminal sanctions may provide incentives for compliance. The effect of these instruments on compliance or environmental performance has been studied extensively in the literature. Given its expectations of firms' responses to monitoring and enforcement, the regulator devises an optimal enforcement strategy for its objective. There are several theoretical papers that examine the optimal enforcement strategy under different sets of assumptions and empirical papers that estimate the effect of enforcement on compliance and environmental performance and the gains from various enforcement schemes.

2.2 Standard Enforcement Model

In order to incentivize compliance, the regulator may monitor firms for violations and punish noncompliers. Firms are typically monitored through inspections and self-reporting which can detect violations perfectly or imperfectly. If inspections can detect violations perfectly, then the probability of an inspection is equal to the probability of detection. If a violation is detected, the regulator may choose to impose a fine. Suppose the firm is risk-neutral and profit-maximizing. The firm will comply with a regulation if the expected costs of noncompliance exceed the benefits. The firm's expected cost of noncompliance is the product of the probability of detection and the punishment for violating. The punishment may include monetary and non-monetary penalties. Suppose that inspections perfectly detect violations so that the probability of inspection equals the probability of detection. Standard economic theory predicts that increasing the probability of inspection or the magnitude of the fine increases the expected costs of noncompliance. Therefore, an increase in the probability of detection or the magnitude of the fine should increase compliance. At the optimum, the expected penalty is equal to the expected harm that arises from the undesirable action. The regulator can reduce enforcement costs by setting the penalty equal to the maximum and lowering the inspection probability such that the expected penalty is equal to the expected harm at the optimum (Becker 1968).

2.3 Inspections

The standard economic model predicts that increasing the probability of an inspection increases the expected costs of noncompliance and therefore, increases the compliance rate. Consistent with this finding, the empirical literature generally finds that inspections increase compliance or improve environmental performance in several contexts. For example, Magat and Viscusi (1990), examine the effect of inspections on compliance with CWA permit regulations for the pulp and paper industry in the early 1980s. Using data from the EPA's permit compliance system (PCS), they find that a past inspection decreases discharge levels and increases the self-reporting of violations. Furthermore, in subsequent periods, they find no evidence of a rebound in discharge levels suggesting that the deterrent effect of inspections may persist. Similar findings are reported for the enforcement of air quality regulations; lagged inspections increase the compliance of steel plants with CAA regulations (Gray and Deily 1996) and with Occupational Safety and Health Administration (OSHA) regulations (Deily and Gray 2007).

Inspections may also have an effect on the severity of a violation. One way in which the severity of a violation is measured is by the size of a violation. For example, a firm is considered to be out of compliance if it is discharge is above the permitted level. The extent to which a firm's discharge surpasses the permitted level may capture the severity of a violation. Environmental performance may be used to measure the severity of a violation (or overcompliance). In the literature, environmental performance is calculated in relative or absolute terms; it may be measured as the ratio of actual emissions or discharge to permitted levels or as the absolute level of emissions or discharge.

Several papers explore the effect of inspections on environmental performance; Magat and Viscusi (1990) find that a past inspection reduces a plant's mean biochemical oxygen demand (BOD) discharges by 20% in the United States. A similar result is observed in the enforcement of water and air regulations in China. Using data on water and air discharges by firms (mostly in the manufacturing sector) in China, Dasgupta et al. (2001) find that inspections decrease the discharge of total suspended solids (TSS) and chemical oxygen demand (COD) in water by 1.18% and 0.40%, respectively and by 0.34% in air. Several other studies arrive at similar conclusions within the context of OSHA regulations (Gray and Jones 1991) and water regulations in Quebec (Laplante and Rilstone 1996).

In addition to increasing the likelihood of compliance and improving environmental performance, inspections may also shorten the duration of a violation. The duration of a violation is of importance to the regulator because lengthier violations may result in greater environmental damages to the public and greater reputational losses to the regulator. Using quarterly data on the compliance of pulp and paper plants with air quality regulations, Nadeau (1997) estimates survival models to examine the effect on inspections on the duration of a violation. The findings indicate that an increase in monitoring, comprised of inspections and tests, significantly shortens the duration of a violation.

Two field experiments examine the effect of changes in the frequency of inspections on compliance. Between 2007 and 2010, the Norwegian Environmental Protection Agency (NEPA) conducted an experiment in which randomly selected groups of firms received a letter informing them of an increase in the frequency of inspections.[1] Contrary to the prediction of economic theory, the experimental results indicate that announcing an increase in the frequency of inspections had no significant effect on compliance (Telle 2013). Similarly, using data from a field experiment in India in which the inspection rate was doubled with the additional inspections being randomly assigned, Duflo et al. (2018) find that an increase in the frequency of inspections does not significantly reduce emissions. However, they do observe an increase in compliance, though the magnitude is small given that inspection frequencies were doubled.[2] A similar conclusion is reached in Eckert (2004) within the context of petroleum storage regulations in Manitoba, Canada; inspections have a significant but small deterrent effect.

A firm's response to inspections may be contingent upon firm characteristics such as its perception of enforcement. Using a survey of chemical manufacturing firms' perceptions of enforcement and CWA permit data, Earnhart and Friesen (2017) find that state inspections have a deterrent effect on firms that perceive enforcement as ineffective but have no effect on the relative discharges of firms that perceive enforcement as effective. This is result is potentially explained by updating; in response to an inspection, firms that perceive enforcement as ineffective my revise their beliefs more than firms that perceive enforcement as effective. Thus, experiencing an inspection may induce a greater change in behavior in firms that perceive enforcement as ineffective.

[1] Randomization was stratified by firm type, size, and potential harm.

[2] Note, inspections may have no significant effect on emissions but a significant, albeit small, effect on compliance if firms near the standard are most responsive to the treatment. However, the effect of inspections is small relative to the increase in the frequency of inspections. One possible explanation for the small effect is that inspections were randomly assigned. If inspections were targeted, it is possible that there would have been larger increases in compliance.

2.4 Fines

The standard enforcement model predicts that an increase in the magnitude of a fine induces greater compliance because it increases the expected cost of noncompliance. Consistent with this prediction, the empirical evidence generally finds that the imposition of a fine and increases in the magnitude of a fine lead to greater levels of compliance. For example, formal enforcement actions, which include fines, consent orders, corrective actions, and remediation requirements reduce the relative BOD discharges of municipal wastewater treatment plants in Kansas (Earnhart 2004b, 2004a). Fines may also reduce the length of time a firm remains in noncompliance; Nadeau (1997) finds that enforcement actions, which include administrative, civil, and judicial actions as well as penalties, reduce duration of time pulp and paper plants spend in violation of EPA air quality regulations.

While these studies provide empirical evidence of the effectiveness of enforcement, they do not distinguish the effect of fines from the effects non-monetary enforcement actions such as court orders, remediation requirements, and information enforcement. Shimshack and Ward (2005), within the context of CWA permit regulations for the pulp and paper industry, separate the differential effects of fines from other enforcement actions; they find that the imposition of a fine significantly reduces future violations. Moreover, they find that fines have spillover effects in that a fine imposed on one plant induces the compliance of other plants. Specifically, an additional fine reduces the average probability of a violation within a regulatory jurisdiction in the subsequent period. While this spillover effect continues to be observed in succeeding years, its effect diminishes over time. Regardless, when considering the spillover effect of fines, fines are more effective at deterring violations than inspections and non-monetary sanctions.

In addition to inducing compliance, fines have been demonstrated to have an effect on the degree of compliance. Shimshack and Ward (2008) find that fines significantly reduce the relative BOD and TSS emissions of pulp and paper plants. Moreover, the quantile regression results indicate that fines cause those already in compliance to over-comply by further reducing their emissions. Furthermore, similar to Shimshack and Ward (2005), the imposition of an additional fine increases the degree of compliance and overcompliance by plants within the state. They find that the driving factors of overcompliance are randomness and jointness of TSS and BOD discharges.

The spillover effect of fines may arise from an increase in the credibility of the enforcement agency's threats. By imposing a fine on a firm, the enforcement agency signals its ability to follow through with its threats and thus may change firms' perceptions about the credibility of its threats. An interesting line of research would be to explore whether similar spillover effects are observed with other regulatory instruments. One would expect that criminal sanctions, due to their severity and saliency, might have spillover effects on the compliance decisions of non-sanctioned firms.

Finally, the standard enforcement model predicts that an increase in the magnitude of a fine increases the compliance rate. Exploiting a revision in the penalty policy for violations of hazardous waste regulations under the Resource Conservation and Recovery Act (RCRA), Stafford (2002) finds that an increase in the fine resulted in an increase in compliance. However, the increase in compliance is small relative to the increase in the fine. One potential explanation for this is that firms did not change their expectations of the penalty by much in response to the revision. This may occur if, for instance, they believe regulators will exercise discretion in their favor.

2.5 Self-reporting

In the United States, several environmental laws require firms to submit self-reports. For example, under CWA permit regulations, firms are required to periodically submit discharge monitoring reports (DMRs) as part of their permit requirements. These reports include the results of samples of the facility's effluent and if there is a violation, an explanation for the cause of the violation and details on the facility's plan to correct the violation. Failure to submit DMRs is considered to be a violation of the permit and the law. Such self-reports are not unique to CWA; they are also required under other major environmental laws such as CAA, the Resource Conservation and Recovery Act (RCRA), and the Environmental Planning and Community Right-to-know Act (EPCRA), to name a few.

Harford (1987) incorporates self-reporting into a standard model of enforcement for emissions standards. A firm will choose a level of emissions such that the marginal cost of abatement equals a weighted mean of the marginal fine rates for violating the reporting requirement and violating the actual standard. The weights on these two components is the probability of detecting a untruthful reports and the probability of detecting a violation of the standard. If the penalty function is convex in the size of the violation, then stronger enforcement of the reporting requirement will result in lower levels of pollution. Furthermore, while increasing fines for violations leads to a reduction in pollution, it may also lead to an increase in misreporting.

Self-reporting may offer several advantages while minimally affecting deterrence if the fine for those who self-report is set equal to the certainty equivalent of the penalty when they do not self-report a violation. Under such conditions, self-reporting reduces enforcement costs by having firms report violations themselves rather than waiting to be detected. Additionally, if firms are risk-averse, then self-reporting may also eliminate risk-bearing costs. Therefore, if the penalty is set to the certainty equivalent of the penalty incurred when firms do not self-report, then welfare is higher in optimal enforcement schemes with self-reporting than those without (Kaplow and Shavell 1994). In a principal-agent framework in which monitoring is imperfect and pollution is stochastic, Malik (1993) finds that in enforcement schemes with self-reporting, firms may be inspected less frequently but must be punished more frequently if found to be out of compliance. In contrast to the findings of Kaplow and Shavell (1994), the effect of self-reporting on the social cost of enforcement is ambiguous.[3] If the monitoring accuracy or the maximum allowable penalty is low, then self-reporting is more likely to reduce enforcement costs. This is because the value of self-reporting is higher when monitoring costs large relative to sanction costs.

The inclusion of self-reporting may have implications for the effects of other enforcement instruments on compliance and other responses to enforcement. When allowing for repeated interaction between the regulator and the firm, Livernois and McKenna (1999) find that under certain conditions, the compliance rate is decreasing in the size of the fine, contrary to the predictions of standard enforcement theory. While lowering the fine may increase the proportion of firms that violate, it may also increase the proportion of violators that are truthful in their self-reporting. If the latter effect outweighs the former, then with self-reporting, lowering the fine may increase compliance.

When there are benefits to remediation, self-reporting may increase efficiency. Recall that the standard enforcement model suggests that the optimal penalty is maximal. However, if there exist remediations benefits that can only be obtained post-detection, the regulator may set the penalty to be below the maximal penalty and increase monitoring so that it can detect more violators and mandate them to clean up. In such a setting, self-reporting offers two advantages: (1) remediation benefits may be obtained absent detection and (2) by setting the penalty for non-reporters to be maximal, a given level of deterrence can be achieved at a lower cost (Innes 1999a).

Self-policing, or taking remediation actions prior to detection, can also increase welfare. A regulator may favorably treat violators that engage in remediation activities to reduce the harm they caused prior to detection. This can be achieved by

[3] This is likely due to sanctions being costless in Kaplow and Shavell (1994) but costly in Malik (1993).

reducing the fine for those who remediate pre-detection just enough to cover the remediation costs. In such an enforcement setting, self-policing allows remediation benefits to be obtained earlier and without costly government mandates (Innes 1999b). This is particularly beneficial if detection is difficult. In response to enforcement, firms may undertake costly avoidance activities, making detection difficult. Self-reporting, in this case, may lower both avoidance costs and the level of enforcement effort required to achieve a given level of compliance (Innes 2001).

Self-reporting of emissions is also a tool used by regulators in transferable emissions permit systems. Similar to the effects of self-reporting in the enforcement of command-and-control regulations, self-reporting may reduce monitoring costs in the enforcement of market-based regulations. The mechanism in which the reduction in monitoring costs is achieved however, is different. With the enforcement of command-and-control regulations, the reduction in monitoring costs is achieved by having to no longer monitor firms that self-report. However, with the enforcement of market-based regulations, the reduction in monitoring costs is achieved by imposing an additional fine on firms who misreport their violations (Stranlund and Chavez 2002).

The empirical literature on self-reporting is scant compared to the theoretical literature. A firm may use self-reporting to signal its cooperation when enforcement is targeted towards past violators. In such an enforcement setting, self-reporting may provide a signal of a firm's cooperation to the regulator and allow it to face a less stringent enforcement regime in the future. Empirical evidence supports this idea; Helland (1998) finds that firms that were detected to have a violation in the recent past are more likely to report a violation in future periods. More recently, using data from natural field experiment in Norway, Telle (2013) find that violations are underreported in self-audits relative to on-site audits, suggesting that while self-audits may reduce enforcement costs, they may also reduce compliance.

2.6 Targeting Enforcement

Given a limited budget, the regulator may induce greater compliance if monitoring and enforcement is targeted to firms that are more likely to violate. Targeted enforcement has been studied extensively in the literature. Targeting may provide an explanation for what is now known as the 'Harrington paradox'—the paradox is that in the enforcement of environmental regulations, high rates of compliance are observed even though expected penalties are typically low relative to compliance costs. While such a result is inconsistent with static models of compliance, it may be consistent with dynamic state-dependent models in which enforcement is targeted towards past violators.

Harrington (1988) develops a dynamic state-dependent model of enforcement in which current violators are placed in a group that faces a more stringent enforcement regime in the future while current compliers are placed (or remain) in the group with a lenient enforcement regime. In this framework, the expected costs of noncompliance include any penalties incurred if found to be out of compliance and the costs associated with being in a stricter enforcement regime in the future. For each group, the regulator chooses the inspection probabilities, fines, and transition probabilities to minimize costs subject to a given compliance level. He finds that the optimal fine is zero in the lenient enforcement regime and maximal in the stringent enforcement regime. Such an enforcement scheme can achieve the same level of compliance that randomized monitoring achieves, but at a lower cost.

The standard state-dependent model of enforcement results in otherwise identical firms abating emissions at different levels. This implies that marginal abatement costs are not equalized indicating that the abatement costs are not minimized. Harford and Harrington (1991) develop a state-independent static model of enforcement that considers abatement costs. They find that for a sufficiently large fine, the static model of enforcement actually achieves a given level of pollution reduction at a lower social cost than the dynamic state-dependent model.

The introduction of asymmetric information into a state-dependent enforcement model leads to different conclusions. The regulator typically does not observe firms' compliance costs; compliance cost is private information held by the firm leading to information asymmetry. Recall that in the standard dynamic state-dependent enforcement model, the fine in the lenient enforcement group is equal to zero while the fine in the stringent enforcement group is set to the maximum allowable penalty. Under the presence of information asymmetries, the optimal fine in the lenient enforcement group depends on the distribution of compliance costs (Raymond 1999). If there is a high proportion of high-cost firms, then it is zero. If, on the other hand, there is a high proportion of low-cost firms, the optimal fine in the lenient enforcement group is the maximum allowable fine.

Most state-dependent enforcement models assume that enforcement is targeted based on a firm's compliance history. While such targeting requires less enforcement resources to achieve a given level of compliance, it is not clear that it is the optimal manner in which to target. In Harrington's framework, violating firms are moved into a group facing more stringent enforcement and can only escape from that group by demonstrating compliance. A targeting scheme in which firms are randomly placed into the group with stringent enforcement and escape when they have demonstrated compliance may provide additional cost savings (Friesen 2003). This is because targeting on the basis of historical compliance status requires that inspections are carried out in the group facing lenient enforcement. With the random movement into the group facing stringent enforcement, inspections are no longer required in the group facing lenient enforcement. Additionally, fewer inspections are required in the group facing stringent enforcement. However, such an enforcement policy is only optimal if the regulator's compliance goal is modest. If the regulator aims to achieve sufficiently high levels of compliance, then the standard state-dependent enforcement model can achieve it at a lower cost.

Another explanation for the Harrington paradox is that regulators sometimes allow for negotiated noncompliance. For example, a regulator may forgive a violation in one domain in exchange for compliance in another. The pursuit of such a strategy by a regulator may be strategic. For some firms, the cost of compliance in each domain is less than the penalty in each domain. Such a firm would violate in both domains if the regulator pursues a policy of full pursuit. However, if the regulator forgives noncompliance in one domain in exchange for compliance in the other, this type of firm may be induced into complying in the domain with a lower compliance cost. If the proportion of firms with compliance costs that are less than the penalty in each domain is low, then offering this regulatory deal can decrease environmental damages (Heyes and Rickman 1999).

The literature on targeted enforcement is largely theoretical.[4] Yet, it is important to know what the gains to a state-dependent enforcement are. A recent empirical paper estimates these gains within the context of the CAA (Blundell, Gowrisankaran, and Langer 2018). In enforcing the CAA, the regulator designates repeat violators as high priority violators (HPV) and threatens them with increased regulatory scrutiny and fines. This is akin to placing violators in the group with a more stringent enforcement regime within Harrington (1988)'s framework. The cost a firm faces by violating include the abatement costs and the increased regulatory scrutiny from being designated as a HPV. Blundell et al. (2018) first estimate the regulatory (from being a HPV) and abatement investment costs that a firm would incur. Then, they use those estimates to construct counterfactual estimates of a firm's investment and compliance decisions if fines for HPVs are no different than those for regular violators under two scenarios: (1) holding the total number of equilibrium fines constant and (2) holding

[4] Eckert (2004) and Nadeau (1997) provide empirical evidence that enforcement is targeted towards past violators and Alberini et al. (2008) find that inspections are targeted toward risky products. However, they do not estimate the value of this targeting.

pollution damages constant. In the first scenario, they find that the number of HPVs, inspections, and pollution damages increase while in the second scenario, they find that fines would have to increase by a substantial amount. Thus, consistent with the theoretical findings, state-dependent enforcement can achieve lower pollution levels at a lower cost.

Recall that the optimal fine in the group facing a stringent enforcement regime is maximal. Thus, an increase in the fine for that group should improve the overall compliance rate by giving firms a greater incentive to comply and avoid being placed in the group with a more stringent enforcement regime. There is empirical evidence consistent with this finding. In 2012, the EPA found the Florida Department of Environmental Protection (DEP) to be inadequately assessing penalties for HPVs of CAA regulations. The EPA's involvement led DEP to impose higher fines for HPVs. Exploiting this natural experiment, Blundell et al. (2020) find that an increase in the penalty for HPVs leads to an increase in the overall compliance rate, including for those who are not designated as HPVs, consistent with the findings of Harrington (1988).

It is worth nothing that much of this discussion has been predicated on the stylized fact that compliance with environmental regulations is high even though the expected penalty is low. It may be the case that inadequate compliance data may lead to overestimated compliance rates. With the aim of obtaining better estimates of noncompliance, the EPA, in the early 2000s, created a representative sample of facilities by randomly inspecting firms for compliance with certain regulations. They found that noncompliance was in fact common; for the three sector-regulation pairs they carried out this exercise for, the noncompliance rates ranged from 34.3% to 61.4% (Giles 2020). Examination of the compliance costs of firms in these sectors would be useful to determine if there is paradox.

Nyborg and Telle (2006) argue that the empirical evidence of the "Harrington paradox" should be treated with skepticism. First, Harrington did not directly observe compliance costs. If marginal abatement costs are sufficiently small, then the compliance rates are not paradoxical. Nyborg and Telle (2006) also do not observe compliance costs. Therefore, using Norwegian enforcement data for the years 1992 through 2001, they focus on classes of violations that have lenient enforcement schemes and classes of violations for which the costs of noncompliance exceed the benefits. In the first scheme, low compliance rates would be consistent with rational crime theory while high compliance rates would be consistent with Harrington's model. In the second scheme, high compliance rates may be consistent with both models. They find that minor violations, for which enforcement schemes are lenient, are widespread, consistent with rational crime theory. Major violations, particularly repeated ones, are rare. This would be consistent with the state dependent enforcement model if compliance costs are high relative to the expected penalty and consistent with rational crime theory if compliance costs are low relative to the expected penalty. Further research that incorporates better compliance data and compliance costs would be useful in determining the true compliance rate and whether the relative sizes of the expected penalty and compliance cost justifies the compliance decision.

2.7 Regulatory Errors

Inspection technology may only be able to imperfectly detect violations. For example, a regulator may fail to detect a violation where one exists or incorrectly detect a violation where one does not exist. This could happen due to uncertainty around measuring emissions; emissions may be incorrectly measured due to laboratory errors, improper sampling, or equipment failure. Thus, firms have imperfect control over their emissions. This type of uncertainty may lead to both under-deterrence and over-deterrence. Under-deterrence occurs since there is a positive probability that a violation will go undetected and in response, firms may increase their level of emissions. Over-deterrence, on the other hand, occurs because there is a positive probability that a violation will be detected where one does not exist and in response, firms may over-comply (Rousseau 2009). Several theoretical papers consider optimal enforcement policies when one or both types of regulatory errors are present.

Suppose inspections give a noisy signal of a firm's emissions and violations are penalized according their severity. If the inspection gives a signal of a firm's emissions beyond some critical value, then an audit, which perfectly detects violations, is triggered. Violators are classified according to the distance between their actual emissions and the critical value that triggers an audit; non-serious violators emit above the standard but below the critical value while serious violator emit above the critical value. If the penalty function is not too steep, tightening the trigger, which corresponds to lowering the threshold that triggers an audit, has two opposing effects on aggregate emissions: (1) induces non-serious violators to reduce their emissions and (2) induces serious violators to increase their emissions. Serious violators increase their emissions because they are at a high enough level of emission where the marginal benefit of abatement, in terms of the fine, is lower. If the penalty function is not too steep, then the increase in emissions will not be offset by the increase in the penalty. Thus, the net effect on aggregate emissions depends on the proportion of non-serious violators and serious violators.

Suppose the regulator is able to improve its inspection technology so that inspections yield a less noisy signal of compliance. In Heyes (2002), a first-stage inspection triggers an audit if it yields a signal of emissions that is greater than some threshold. In such a setting, an improvement inspection technology has an ambiguous effect on aggregate emissions. Firms whose actual emissions is close to the signal the inspection provides have an incentive to reduce their emissions while those whose emissions are farther away do not. Therefore, firms whose actual emissions is far away from the signal may emit more. Additionally, violators who emit above the standard but below the threshold that triggers an inspection will increase emissions. This is because for such firms, an improvement in the inspection technology reduces the probability of a second stage audit being triggered, and thus lowers their expected penalty. Thus, the net effect on aggregate emissions depends on the distribution of firm types. In contrast, Alberini et al. (2008), within the context of Hazard Analysis and Critical Control Points (HACCP) programs in seafood processing, find that firms that expect to face more precise inspections are more likely to comply. The difference in results likely arises from differences in the enforcement settings of the two papers. Enforcement has one stage in Alberini et al. (2008) but two stages in Heyes (2002) and an improvement in the inspection technology affects the probability of a second stage audit differently for different firms.

When regulatory errors are present, the cost savings from targeted enforcement may be diminished. Consider a state-dependent enforcement model in which the regulator chooses the standard, fine, and inspection frequency to minimize the sum of monitoring and enforcement costs, abatement costs, and environmental damages. Even with measurement error in measuring pollution, the dynamic state-dependent model outperforms the static state-independent model. However, in contrast to the state-dependent model without measurement error, the optimal fine in the group facing the lenient enforcement regime is greater than zero when regulatory errors are present (Harford 1991).

2.8 Warnings

A majority of the EPA's enforcement activities result in a warning (Esworthy 2014; Harrington 1988). If a firm moves to comply upon receiving a warning, no further actions are typically taken. Yet, even with most enforcement actions resulting in a warning, high levels of compliance are observed. There are only a few theoretical papers that examine the role of warnings in the enforcement of environmental regulations and one empirical paper. While warnings are not explicitly modeled in Harrington (1988), the act of being moved into the group with a stringent enforcement regime can be interpreted as a warning. Since the optimal fine in the group facing a lenient enforcement regime is zero, firms are not fined until they are moved into and violate in the group with a stringent enforcement regime. Thus, in moving violators to the group with a stringent enforcement regime, the regulator is essentially warning them that they will face a higher inspection probability and a fine in the next period. There is empirical evidence that warnings serve as such a signal to the firm; Eckert (2004) finds that a warning in the current period is associated with a significant increase in the probability of an inspection in the next period.

It is important for the regulator to have control over the regulatory environment. As the number of violators increases, the regulator's budget constraints increasingly limit its ability to pursue sanctions against violators. Consequently, the credibility of the threat of punishment may decrease as the number of violators increases. Beyond a critical number of violators, Nyborg and Telle (2004), in a setting the regulator's budget is exogenous, find that sanctions are no longer sufficient at deterring violations because the threat of harsher future sanctioning is no longer credible. The critical value is higher when the regulator uses warnings because then, it does not have to sanction all violators, only those who violate after receiving a warning. There are two Nash equilibria: (1) a full-compliance equilibrium in which all firm comply and the expected fine exceeds compliance costs and (2) a no-compliance equilibrium in which no firm complies and the expected fine is lower than the cost of compliance. If firms might violate by mistake, warnings can reduce the probability of the number of violators exceeding the critical value at which future enforcement becomes incredible and thus reduce the probability of switching from a full-compliance equilibrium to a no-compliance equilibrium.[5]

[5]This result relies on the assumption that it is costly to switch between compliance and noncompliance, delaying compliance is not beneficial, and detection probabilities are sufficiently large.

In Nyborg and Telle (2004)'s theoretical model, it is never optimal for a firm to delay compliance until receipt of a warning. In fact, that strategy is strictly dominated by one in which the firm plans to comply but if there is an error, does not attempt to correct it. This is because in their model, a firm that receives a warning must pay a verification cost, in addition to the compliance cost, to demonstrate compliance. Therefore, strategy of delaying compliance until a warning comes with a probability of having to pay these verification costs. Thus, the warning is a costly signal to the firm that it will face a future audit. This result is consistent with the findings of Blundell et al. (2018) that being designated as a HPV is costly to the firm.

However, there may exist scenarios in which warnings are a costless signal to a firm that it will be subject to regulation. Consider a setting in which there are information gaps in the regulator's knowledge of the universe of regulated firms (USEPA 2005). In such a setting, the regulator has to choose to target enforcement towards newly discovered firms and/or known firms that have violated. For newly discovered firms, whether or not there are gains to targeting depends on their reason for being unknown to the regulator. If they are unknown to the regulator because they are concealing themselves, then there may exist gains to targeting enforcement towards them. However, if they are unknown to the regulator because they themselves are unaware they are subject to regulation, then it is unclear whether any gains exist. This is because they may be firms that would comply had they known they are subject to regulation. This is a line of research that merits further investigation.

Nyborg and Telle (2004) consider an error in which the firm mistakenly violates. However, warnings may also be useful when the regulator imperfectly detects violations; for example, a regulator may falsely detect a violation where one does not exist or fail to detect a violation where it does exist because of the uncertainty around measuring emissions. Recall that this uncertainty can lead to both over-deterrence and under-deterrence. In such settings, the use of warnings has two effects: (1) it reduces overcompliance and the number of unjust prosecutions and (2) it increases underdetterence. If the correction of over-deterrence outweighs the increase in under-deterrence, then warnings can reduce the impact of regulatory errors and improve welfare (Rousseau 2009).

2.9 Endogenous Inspections, Fines, and Maximum Penalty Sizes

The standard enforcement model assumes that firms are not able to influence the ability of an inspection to detect a violation. Absent the ability to engage in activities that reduce the ability of an inspection to detect a violation, an increase in the frequency of inspections results in an increase in environmental efforts, consistent with the predictions of standard enforcement models. However, when firms are able to engage in concealment activities making the probability of detection endogenous, an increase in the frequency of inspections has two opposing effects on environmental effort: (1) a positive effect by making noncompliance more likely to be detected and (2) a negative effect by making investment in concealment technologies more attractive. Therefore, in such a setting, policies should favor making inspections more thorough rather than frequent (Heyes 1994).

Making inspections more thorough may improve the detection capability of an inspection. Given a number of inspectors, the regulator may choose to increase the frequency or intensity of inspections. For example, the regulator may choose to send more inspectors to a facility or fewer inspectors to more facilities. An enforcement agency may send a team of inspectors to a facility with the hopes of reducing corruption and improving detection capabilities. Muehlenbachs et al. (2016) examine the impact of team inspections on compliance with operational guidelines for offshore production sites in the Gulf of Mexico. Exploiting exogenous variation in team size driven by weather-related impediments to travel, they find that increasing the intensity of inspections by adding additional inspectors to the team significantly increases the number of sanctions, consistent with the theoretical findings of Heyes (1994).

The maximum penalty that can be imposed may also be endogenous. Firms may challenge the penalty in court which makes the fine costly to impose. In such a setting, an increase in the fine may not necessarily result in greater compliance. This is because an increase in the penalty leads to two competing effects: (1) an increase in the expected cost of noncompliance increases a firm's incentive to comply and (2) the increase in the severity of the fine gives firms a greater incentive to challenge the fine (Kambhu 1989). Thus, the net effect on compliance depends on the magnitudes of these effects. When firms are able to challenge the fine, a policy that lowers the cost of compliance may be more favorable (Nowell and Shogren 1994). This is because such a policy would incentivize compliance while leaving a firm's incentive to challenge enforcement unaffected.

Limits on a firm's liability may dampen its response to monitoring and enforcement. It may be infeasible to set the penalty at a sufficiently high level so that the expected penalty equals the expected harm at the optimal. The maximum penalty may be restricted by the wealth of the violator, political considerations, legal considerations, and firm behavior. For example, a firm may not be held liable for an amount that exceeds its assets. This may provide firms with an incentive to shift activities that cause environmental harm to smaller subsidiaries that have fewer assets and thus can be held liable for less. Ringleb and Wiggins (1990) examine this within the context of liability applications to latent hazards. They proxy for expected liability using worker exposure to occupational hazards and find that an increase in worker exposure results in a significant increase in the number of small firms entering the hazardous sectors of the economy. Similarly, Alberini and Austin (1999), within the context of the Federal Superfund law, find that small firms are positively associated with more spills. This is potentially explained by larger firms shifting environmentally risky activities to smaller, “judgement proof” firms to lower liability costs thereby making the maximum penalty endogenous.

A firm’s financial status, which determines its ability to pay the penalties associated with noncompliance, may influence its response to monitoring and enforcement. Using panel data and instrumental variable techniques, Earnhart and Segerson (2012), examine the effect of the interaction between financial status—solvency, illiquidity, and profitability—and sanctions. They find that an increase in profitability and solvency make sanctions more effective at reducing relative discharges. Since solvency and profitability determine a firm’s ability to pay the penalty, it affects their calculation of the expected costs of noncompliance. The sting of the penalty is felt more by firms that are better able to pay it.

2.10 Publicized Violations

Several environmental laws allow a regulator or a private citizen(s) to pursue a civil or criminal lawsuit against a firm that violates an environmental regulation. The threat of these types of lawsuits, in theory, increase the expected cost of noncompliance and thereby make compliance more likely. The empirical literature provides evidence that lawsuits deter violations. Within the context of CAA regulations, Keohane et al. (2009), within the context of CAA lawsuits between 1996 and 2000, find that electric power plants that perceive a high likelihood of future lawsuits reduced their emissions. Similarly, Almer and Goeschl (2010), using data on German environmental crime and resulting sanctions between 1995 and 2005, find that criminal sanctions have substantial deterrent effects. Moreover, the publicity of the sanctioning has a deterrent effect that is greater than the probability of conviction or the magnitude of the sanction.

One potential reason is that the publicizing of these types of enforcement actions can result in de facto penalties in terms of loss of market value (Muoghalu, Robison, and Glascock 1990). This finding is similar in spirit with the effects of information disclosure regulations on compliance. For example, utilities that were required to mail consumer confidence reports (CCRs) directly to consumers as part of their compliance with the Safe Drinking Water Act (SDWA) significantly reduced total violations (Bennear and Olmstead 2008). Similar to the findings of Almer and Goeschl (2010) for criminal sanctions, Foulton et al. (2002) find that public disclosure programs in British Columbia have a greater effect on compliance and environmental performance than orders, fines, and penalties.

Several environmental laws also permit citizens to pursue civil or criminal lawsuits. Since the regulator has a limited enforcement budget, private enforcement by harmed and interested parties may provide deterrent effects. Empirical evidence finds that private citizen suits indeed have deterrent effects (Langpap and Shimshack 2010). However, allowing private enforcement may have unintended consequences. For example, if the regulator gives regulatory deals in which it forgives noncompliance in one domain in exchange for compliance in another domain, private suits in the domain where noncompliance is forgiven may undermine the incentives of the regulatory deal (Heyes and Rickman 1999). In this instance, allowing private suits may increase the costs of monitoring for a given level of pollution.

Another potential unintended consequence of allowing private enforcement is that it may crowd out public enforcement. Given a limited budget, a regulator may choose to withhold resources where private enforcement activities are pursued. Empirical evidence indicates that private enforcement crowds in public monitoring but crowds out public enforcement actions such as warnings, formal consent degrees, and fines (Langpap and Shimshack 2010). This study examines the relationship between public and private enforcement. An interesting line of research would be to examine the general deterrence effects of private enforcement suits. If general deterrence effects exist and are sufficiently high, it may justify allowing private citizen suits.

2.11 Conclusion

The literature on the enforcement of environmental regulations examines the optimal enforcement policy in various enforcement settings including instances where information is incomplete. These include scenarios in which the monitoring probability is less than one so that the regulator observes the compliance status of a subset of firms, when monitoring technologies are imperfect and detect compliance status with error, and when there exist information asymmetries about compliance costs. One aspect that the literature does not consider is incomplete information about the universe of firms subject to regulation. Obtaining a complete census of the universe may be difficult for two reasons: (1) it may be difficult to initially obtain information on the identities of the relevant agents, particularly if the regulated universe is vast and (2) it may be difficult to maintain up-to-date information over time, particularly if turnover is high. As a result, the regulator may partially rely on self-identification to obtain information on the universe of regulated firms; when firms apply for any required permits to pollute, they are essentially identifying themselves as belonging to the regulated universe. However, firms have an incentive to remain unknown to the regulator because if they are unknown, then they will not be subject to monitoring and enforcement and incur the associated costs.

The next two chapters examine the effect of incomplete information about the identities of the relevant agents on a firm's compliance decision and on ambient environmental quality. The third chapter examines the effect of incomplete enforcement information on farm compliance with nutrient management regulations in Maryland. The results indicate that an increase the share of farms known to the regulator results in a significant decrease in the likelihood of compliance. If incomplete enforcement information has a negative effect on compliance, then it may also have consequent effects on ambient environmental conditions. The fourth chapter examines the effect of incomplete enforcement information on ambient water quality within the context of CWA permit regulations in the Mississippi River Basin. The results indicate that an increase in the share of facilities known to the regulator results in a significant decrease in ambient pollutant concentration for three of the four pollutants modeled. Thus, incomplete enforcement information has implications for both compliance and ambient environmental quality. It would be worthwhile for future work to examine the optimal policy in settings where the regulator may be unaware of the existence of some firms.

3 Regulatory Compliance under Enforcement Gaps

3.1 Introduction

The effectiveness of regulation depends on the extent to which regulated firms comply, which depends in turn on how firms perceive the benefits and costs of compliance. Some of those benefits and costs are transmitted through markets, e.g., via changes in stock prices or reputational influences on demand for a firm's products. Most of those benefits and costs, though, come from enforcement actions by regulatory agencies. Regulators typically have limited resources for enforcement but the literature to date has shown that even with those limitations a wide variety of instruments—including inspections, warnings, penalties, and sanctions—can be effective in inducing compliance (for reviews see Cohen 1999; Heyes 2000; Polinsky and Shavell 2007; Gray and Shimshack 2011; and Shimshack 2014).

One aspect of enforcement that has been largely overlooked in the literature to date is the fact that regulators may not know of all of the firms in an industry that are subject to regulation. A recent study by the United States Environmental Protection Agency's (EPA's) Office of Inspector General, for example, found significant gaps in the Agency's enforcement arm's knowledge of entities regulated under most major environmental legislation (USEPA 2005). The existence of such enforcement gaps should not be a surprise. Exit of old firms and entry of new ones is a standard feature of competitive economies. Turnover of firms is widely understood to be a key mechanism of the process of "creative destruction" driving innovation and growth. Keeping up to date on industry composition requires devoting regulatory resources to monitoring entry and exit. Updating registries of regulated firms may not be a priority in light of budgetary and personnel constraints.

These enforcement gaps may be quite large, as changes in the composition of firms in an industry are quite common. Exit and entry rates in manufacturing, for instance, are 7-8 percent annually and the 5-year survival rate of new startups is only 55 percent. Exit and entry rates of mining firms are higher, around 11-12 percent annually, with a 5-year survival rate of startups correspondingly lower at only around 45 percent. Exit and entry are substantial even in agriculture, where the image of the family farm passed down through generations is a staple of public imagination: Exit and entry rates of farming, fishing, and forestry businesses run around 9 percent annually, with a 5-year survival rate of new startups around 65 percent (Bureau of Labor Statistics 2019; Deutsch 2017).

Industry turnover tends to create gaps in regulators' knowledge of the universe of firms subject to regulation. For example, in 2005, when the US EPA's Office of Inspector General (OIG) compared current data with the official registry of regulated entities used by the Agency's Office of Enforcement and Compliance Assurance (OECA), it found that the number of entities that ought to have been regulated under six major regulatory programs was 35 percent greater than the number in OECA's database containing the universe of regulated entities under those programs (USEPA 2005). A subsequent analysis of the Lead-Based Paint Renovation, Repair, and Painting Rule came to a similar conclusion (USEPA 2019).

This paper conducts a theoretical and empirical analysis of a firm's compliance strategy when such enforcement gaps are present. We develop a theoretical model of a firm's compliance decision in a setting typical of regulations in a variety of health and safety contexts, including HACCP regulations governing food safety, quality of care in nursing facilities, workplace occupational safety, Affordable Care Act regulations governing health data security, and conservation compliance in agricultural subsidy programs (wetlands and highly erodible land protection requirements). These regulations depend heavily on record keeping. The compliance decision consists of two components: (1) developing a formal compliance protocol and (2) implementing and adhering to that compliance protocol. Determining whether a firm has developed a compliance protocol involves checking whether the firm has developed a set of written procedures that meet regulatory standards. Periodic inspections of firms' records and facilities are then used to determine whether the firm has followed those protocols. Failure to comply with either component initially results in a warning, with subsequent violations resulting in fines. We show that in the absence of enforcement gaps (i.e., if the regulator has a complete census of the regulated industry), the firm's optimal strategy will be to develop a compliance protocol but not implement it until inspected and warned. However, the optimal strategy for a firm believing it has a sufficiently low probability of being subject to enforcement will be to delay developing a protocol until warned and then delay implementation until being inspected and warned.

We analyze the effect of enforcement gaps on the compliance protocol development component of regulations empirically in the context of the Maryland Water Quality Improvement Act of 1998 (WQIA). The WQIA requires farms meeting certain criteria to develop, file, and implement a nutrient management plan (NMP). The registry of farms used by the Maryland Department of Agriculture (MDA), which enforces this regulation, includes only a subset of the farm operations in Maryland that are required to comply with this regulation. Our econometric model indicates that the probability of being included in the MDA farm registry is associated with a statistically significant and economically meaningful increase in the probability of filing a NMP for farms required to have a NMP. This result is robust to a variety of specifications of the probability of inclusion in the MDA farm registry and the inclusion of covariates. Additionally, we present suggestive evidence that farms delay compliance with the implementation requirement of the WQIA until inspected and warned.

The rest of the paper is organized as follows. Section 3.2 reviews the relevant literature. Section 3.3 presents a theoretical analysis of the impact of enforcement gaps on firm compliance strategy. Section 3.4 discusses the institutional background of the WQIA. Sections 3.5 and 3.6 present the data and econometric model used in the empirical analysis. Section 3.7 discusses the results of our econometric analysis. Section 3.8 concludes.

3.2 Literature Review

When compliance is not privately optimal for firm, regulators may incentivize compliance by monitoring and penalizing firms for noncompliance (see for example Shimshack 2014). Monitoring and enforcement actions are typically rationed because they are costly and regulatory agencies have limited resources. Thus, firms' compliance strategies are shaped by their beliefs about the likelihood of being detected in a state of noncompliance and about the sanctions they will incur upon detection. Specifically, economic theory suggests firms will comply with an environmental regulation so long as the expected costs of noncompliance exceed the expected benefits (Becker 1968). The expected benefits of noncompliance include avoiding the direct and indirect costs associated with compliance. The direct costs of compliance are comprised of internal and external costs associated with developing a compliance protocol, expenditures on equipment required by the protocol, operation and maintenance costs involved in keeping that equipment running and in good working order, etc. Indirect costs include higher expenses due to the redesign of production processes, reductions in productivity, and lost output when the compliance protocol is implemented. The expected costs of noncompliance include fines, penalties, expenses associated with more intensive regulatory scrutiny, financial impacts arising from a tarnished public image, and negative spillovers onto other aspects of a firm's operations due to a poor relationship with various levels of government.

Standard economic theory on firms' responses to regulatory enforcement establishes that inspections and penalties are close substitutes, as the expected cost of noncompliance is simply the product of the probability of detection and the penalties incurred upon detection. When penalties are limited, compliance can be influenced by altering the frequency with which firms are inspected (Becker 1968, Polinsky and Shavell 2000). Firms may respond by undertaking avoidance activities that make detection more difficult (Malik 1990, Bebchuk and Kaplow 1993, Heyes 1994). When firms invest in technologies that serve to reduce the probability a violation is detected during an inspection, regulators may need to respond by making inspections more thorough (Heyes 1994). Conversely, firms may choose to heighten compliance effort when inspections are subject to measurement error (McClelland and Horowitz 1999, Alberini et al. 2008, Rousseau 2009; Malik 2014). Inspections may also serve as a signal of the firm's true emissions level and trigger an audit if the signal is greater than some threshold (Heyes 2002). However, in such a setting, both a change in the threshold and a change in the inspection technology have an ambiguous effect on emissions. Since inspections are costly, regulators can reduce enforcement costs by creating incentives for regulated firms to self-report rather than waiting to be inspected (Malik 1993, Kaplow and Shavell 1994, Livernois and McKenna 1999). The desirability of incentives for self-reporting are especially great when firms engage in avoidance behaviors (Innes 1999a, 1999b, 2001).

In the enforcement of environmental regulations, high levels of compliance are observed even though the expected penalty of most regulations is low relative to the compliance costs (Harrington 1988). While such a result is inconsistent with rational crime theory (Becker 1968), it is consistent with a dynamic game in which more stringent enforcement is targeted towards past violators (Harrington 1988) or settings in which the regulator forgives a firm's violation in one domain in exchange for compliance in another domain (Heyes and Rickman 1999).[6]

The empirical literature provides evidence that, as expected, fines are effective

[6] The regulator may interact with a firm along multiple dimensions. For example, a regulator may enforce different regulations on the same firm. In this case, each regulation would be a different dimension along which the regulator interacts with the firm.

in inducing compliance (Earnhart 2004b; Glicksman and Earnhart 2007). There is also evidence that the threat of a penalty induces compliance; within the context of the US pulp and paper industry, for example, Shimshack and Ward (2005) find that while fines imposed on a single plant have minimal impact, the "regulator reputation" spillover effect from a regulator imposing a fine on plants within a regulatory jurisdiction has a positive, statistically significant, and economically meaningful effect on the likelihood of compliance by other plants within the same regulatory jurisdiction. As previously discussed, standard economic theory suggests that an increase in the magnitude of a fine increases the expected cost of noncompliance. Consistent with this finding, Stafford (2002) finds that a federally mandated increase in the allowable financial penalties for noncompliance significantly reduced firms' violation probabilities, though the increase in compliance was small relative to the increase in the allowable penalties. However, if firms are able to challenge a fine, then an increase in the fine may not necessarily induce greater compliance (Kambhu 1990; Nowell and Shogren 1994).

Other potential consequences of being found out of compliance have also been shown to increase the likelihood of compliance. In some cases, the prospect of standing trial by itself has been found to be more of a deterrent than the probability of conviction or the magnitude of the fine (Almer and Goeschl 2010). Being sued for mismanagement of hazardous waste under the Resource Conservation and Recovery Act (RCRA) or the Comprehensive Environmental Response Compensation and Liability Act (Superfund) has similarly been shown to result in de facto penalties in terms of loss of market value (Muoghalu et al. 1990).

While fines and sanctions seem to be effective at deterring violations, they are costly and are imposed relatively rarely (Esworthy 2014). As noted above, inspections have been shown to be close substitutes for financial and non-financial penalties. There is extensive evidence that the threat of inspection reduces the likelihood of a violation. This result has been observed in a variety of contexts, including water pollutant emissions from the pulp and paper industry (Magat and Viscusi 1990, Laplante and Rilstone 1996, Helland 1998) and municipal wastewater treatment plants (Earnhart 2004b); air pollutant emissions (Telle 2009, Lim 2016); compliance with food safety regulations in seafood processing plants (Alberini et al. 2008); hazardous substance regulations in Norwegian manufacturing plants (Telle 2013); and petroleum storage regulations at storage sites in Canada (Eckert 2004).

After detecting a violation, regulators may issue a warning rather than a fine. Warnings are used extensively in the enforcement of environmental regulations; most of the EPA's audits result in a notice of violation rather than an immediate penalty (Harrington 1988) and several states impose a penalty only when firms refuse to correct violations or prove to be uncooperative (Russell 1990). Theoretical arguments suggest that warnings can deter future violations through the threat of stronger enforcement (Eckert 2004). Empirical evidence provides confirmation. Using data on the enforcement of environmental regulations of petroleum storage in the Canadian province of Manitoba, Eckert (2004) finds that a warning at last inspection increases the probability of a subsequent inspection. This result suggests that firms who received a warning in the previous period are more likely to be inspected in the current period, consistent with the idea that a firm may face a more stringent enforcement regime in the current period if it was found to be out of compliance in the previous period. Therefore, assuming that firms are not myopic, warnings may deter future violations through the associated threat of a more stringent enforcement regime.

Theoretical and empirical studies to date all treat the threat of inspection as determined with complete knowledge about the number and identities of the firms subject to regulation. But, as noted above, constant exit and entry of firms makes it costly to maintain complete registries of regulated firms and regulatory agencies may choose to allocate their limited resources elsewhere. The effects of the resulting enforcement gaps on regulatory compliance have not been investigated in the literature to date. In what follows, we examine theoretically a firm's compliance strategy in a setting where the enforcement agency does not know the number and identities of the regulated agents. We then test the predictions of that theoretical analysis using data on the enforcement of Maryland's regulations governing nutrient management in agriculture.

3.3 Theoretical Framework

This section develops a theoretical model of the optimal response of the firm in the presence of enforcement gaps. We use a standard model with costly enforcement and limited liability. We present a model of a firm's compliance decision in a setting typical of environmental and health and safety regulations, where the compliance decision consists of two components: (1) developing an initial compliance protocol and (2) implementing and adhering to that compliance protocol.[7] Failure to develop a compliance protocol initially results in a warning, with subsequent violations resulting in a penalty, P_F. Once a protocol has been developed, inspections are used to determine whether implementation of the compliance protocol is adequate. Firms that complied with the protocol development component of the regulation are inspected with probability q_1 while firms that did not are inspected with probability q_2. Given a limited budget, a regulator is likely to find it optimal to target inspections towards

[7]This form of regulation is common in the health and safety context, among others. Food safety regulations based on the Hazard Analysis of Critical Control Points (HACCP) concept, of instance, require firms to develop detailed plans for (a) ensuring that food does not become contaminated during processing and (b) for handling any incidents of contamination that may occur. Periodic inspections are used to determine whether acceptable plans are in place and whether observed equipment and operating procedures are consistent with that plan. Regulations governing occupational safety, protection of patient medical data, and quality of care in skilled nursing facilities have the same general structure. Recipients of farm subsidies are required to have in place a conservation plan approved by local Natural Resource Conservation Service or soil conservation district technicians; failure to comply can result in loss of access to new subsidies and, in some cases, demands to repay subsidies already received. The equivalent two-stage process in some industries consists of (1) installing pollution control equipment (e.g., smokestack scrubbers) and (2) keeping that equipment in operation at all times it is needed.

firms that have not complied with the requirement to develop a plan, as such firms can be presumed to be more likely to fail to implement their plan after developing it. Therefore, we assume $q_2 > q_1$. Again, noncompliance initially results in a warning with subsequent violations resulting in a fine, P_C. Compliance is costly to the firm; firms incur a cost F in developing and a cost C in implementing the compliance protocol. Assume $0 < P_F < P_C$, $P_F > F$, and $P_C > C$.[8]

When enforcement gaps are present, there is a probability $k \leq 1$ that the firm is known to the regulator, with $k < 1$ for some firms. The firm's decision tree is presented in Figure 3.1. At the first decision node, the firm faces three options: develop a protocol and implement it, develop a protocol and do not implement it, or do not develop a protocol and do not implement it. If a firm chooses to develop a protocol and implement it, it will incur a cost of $F + C$. If a firm chooses to devise a compliance protocol but then not implement that protocol, it will be inspected with probability q_1. If inspected, the firm will be warned and must then decide to comply or disregard the warning. If it complies, it will incur a cost of $F + C$. If it disregards the warning and is inspected, it will incur a cost of $F + P_C$. If an inspection does not occur, it will only incur F. If warned, it is easy to see that a firm will comply rather than disregard the warning because $F + C < F + P_C$.

Next, consider a firm that initially does not develop a compliance protocol and therefore does not implement it. Then with probability k, such a firm will receive a warning from the regulator to develop a compliance protocol. After the warning, the firm is faced with the same choices as in the first decision node. Again, if it develops a compliance protocol and implements that protocol, it will incur a cost of $F + C$. If it does not develop a compliance protocol and thereby does not implement one, it

[8]We make this assumption so that the firm's strategic considerations conform to the observed fact that compliance rates are typically high even though nominal penalties are often low relative to compliance costs (Harrington 1988, Heyes and Rickman 1999). Additionally, fines for noncompliance are typically cumulative and thus exceed compliance costs when a firm has remained noncompliant for a long enough period of time.

will have to pay both penalties, $P_F + P_C$.[9] If the firm does not receive a warning for failing to develop a compliance protocol, then it will incur no costs. Suppose the firm develops a protocol after receiving a warning but does not implement it. Such a firm will be inspected with probability q_2, and if inspected, will receive a warning. The firm must then decide to either comply or disregard the warning. As before, it will comply rather than disregard the warning because $F + C < F + P_C$.

It is clear from Figure 3.1 that it is never optimal for a firm to "develop and implement" at the first decision node because both "develop and do not implement" and "do not develop and do not implement" strictly dominate "develop and implement" ($F + q_1C < F + C$ and $k(F +_2 C) < F + C$, respectively). Whether or not "develop and do not implement" dominates "do not develop and do not implement" depends on the value of k. Established firms and firms that have been subject to enforcement action in the past will expect to be included in the regulatory agency's registry and thus act as if $k = 1$. Newer firms and firms that have not experienced enforcement actions in the past may act as if $k < 1$. Firms with sufficiently high perceived values of k, specifically $\frac{F+q_1C}{F+q_2C} < k \leq 1$, will also behave as if they are known to regulators, choosing to develop a protocol, but only implementing it if inspected and warned. This choice is identical to the strategy a firm would choose when $k = 1$, i.e., when the firm knows with certainty that it falls under regulatory purview. Firms with a sufficiently low perceived probability of being known to the regulator, specifically, $k \leq \frac{F+q_1C}{F+q_2C} < 1$, will choose to not develop a compliance protocol and then, if warned, develop one but not implement it until inspected and warned. Thus, the lower the perceived likelihood of being subject to enforcement (represented by a lower value of k), the greater the likelihood a firm will fail to comply with the protocol development component of the regulation. This analysis suggests that: (1) firms that are subject to regulation and believe they are less likely to be subject to enforcement gaps are more

[9] We are ruling out the case where a firm does not file but complies with a protocol as that option is strictly dominated.

likely to develop an initial protocol and (2) firms will tend to delay implementation until inspected and warned.

With respect to the first result, a decrease in likelihood of being known to the regulator essentially reduces the expected cost of noncompliance. The firm's expected cost of noncompliance when it chooses to not develop a protocol is $k(F + q_2C)$. It is clear that a decrease in the likelihood of being known to the regulator, i.e., a decrease in k, serves to reduce the expected cost of noncompliance. The lower the probability of being known, the greater the incentive for firms to delay the development of a compliance protocol until discovered. In the case where $k = 1$, i.e., when firms are included in the regulator's registry with certainty, firms do not have the incentive to delay the development of an initial protocol because, with certainty, they will face higher implementation inspection probabilities and therefore, higher expected costs. For the firm's compliance decision, the relevant inspection probability is the conditional probability of inspection given that the regulator is aware that the firm is subject to regulation. Since a regulator must know that a firm falls under the purview of the regulation in order to inspect it, it must be the case that, if the probability of being known is strictly less than 1, then the firm's conditional probability of inspection given that it is known to the regulator is strictly greater than the unconditional probability of inspection. Additionally, this probability of inspection conditional on being known approaches the unconditional probability of inspection as enforcement gaps shrink (i.e., as k approaches 1).

With respect to the second result, even if a firm knows the regulator is aware that it is subject to regulation, it will have an incentive to delay compliance until warned. The firm knows that, before the regulator determines whom to inspect, there is a possibility that it can choose to not comply and face no penalty. Additionally, if inspected, the firm knows it will initially only receive a warning. If receiving a warning is costless to the firm, then the firm has an incentive to delay compliance until inspected and warned. At that point, the firm knows for certain that a continuing violation will result in a penalty. Therefore, if the detection of a violation results in a warning that is costless to the firm, then the firm is better off waiting to come into compliance until inspected. Because this second result only depends on warnings being costless to the firm, it will hold for all values of k.[10]

The preceding analysis assumes that penalties for non-compliance are set exogenously. It may, however, be possible for firms to take actions that influence penalties, for example, by engaging in protracted negotiations with regulators, mounting legal challenges to the regulation, and similar means. It is worth noting that the firm's optimal choices of whether to file a protocol and whether to implement that protocol remain unchanged as long as the sum of the penalty and the cost of resource expended influencing that penalty remain greater than the respective costs of compliance.

3.4 Institutional Background

We examine the consequences of enforcement gaps empirically in the context of nutrient management regulations imposed under the Maryland Water Quality Improvement Act of 1998 (WQIA). The WQIA was passed to protect the Chesapeake Bay from agricultural nutrient loadings that could contaminate both surface water and groundwater. About 40 percent of the nitrogen and 50 percent of the phosphorus polluting the Bay comes from agricultural runoff (Chesapeake Bay Foundation 2017). Nutrient runoff from agriculture may result in eutrophication, decreased biodiversity, and altered species composition/dominance (Chislock et al. 2013). The Chesapeake Bay is an important part of the economy of several states. In 2009 alone, the Bay region generated benefits valued at $107.2 billion (Phillips and McGee 2016). The State of Maryland has a longstanding commitment to improving water quality in the Bay and its tributaries. The WQIA is intended to help the State achieve this goal by

[10] If a firm is able to reduce the penalty (plus the cost of effort expended on reducing the penalty) below the cost of compliance, it will be optimal for the firm to remain out of compliance indefinitely.

reducing nutrient runoff from farms through improved management of fertilizers and manure, the principal sources of agricultural nutrient emissions.

Under the WQIA, agricultural operations that use commercial fertilizer and have annual farm sales of \$2,500 or more or eight or more animal units are required to develop and implement a nitrogen- or phosphorus-based NMP.[11] The goal of nutrient management planning is to balance soil nutrient inputs with crop nutrient uptake requirements in order to reduce nutrient runoff into water bodies. Components of nutrient management plans include chemical analysis of soil and manure, assessment of the nutrients contributed by leguminous crops, evaluation of past management practices, determination of fertilizer application and timing, and establishment of yield goals. Additionally, agricultural operators must submit Annual Implementation Reports (AIRs) every year that include information about the amounts of fertilizers applied to each crop as well as other relevant information about the farm operation. The MDA uses the AIRs to evaluate each operator's implementation of his or her plan. The environmental benefits gained from nutrient management planning are a function of the extent of compliance with NMPs, which in turn is determined by the incentives for compliance faced by firms.

The WQIA specifies measures MDA must take in enforcing nutrient management plan regulations. An operator that fails to file a NMP by the deadline is subject to a written warning for a first violation and an administrative penalty of no more than \$250 for any subsequent violations (WQIA §15.20.07.07A). An operator who fails to implement a plan by the implementation deadline is subject to a written warning for a first violation. If an operator fails to comply with the plan implementation requirements after a reasonable period of time following the warning (90 days), an operator is subject to an administrative penalty for any subsequent violations of no

[11] Animal units are defined as follows: 1 beef cow = 1 animal unit, 1 bird = 0.008 animal units, 1 dairy cow = 1.25 animal units, 1 pig = 0.4 animal units, 1 sheep/goat/lamb = 0.1 animal units, and 1 horse = 2 animal units.

more than \$100 per violation per day up to a yearly maximum of \$2,000 per operation per NMP. Daily penalties do not continue to accrue as long as the operator takes reasonable steps to correct the violation (WQIA §15.20.07.07D).

Failure to comply with nutrient management regulations can also impose indirect costs on violators in addition to any incurred fines. The Maryland Agricultural Water Quality Cost-Share Program (MACS) provides farmers with grants that cover up to 87.5 percent of the installation costs of certain conservation practices. Farms that have (a) not submitted an AIR, (b) not paid a fine for failing to implement an AIR, or (c) have not corrected deficiencies in their NMPs within 90 days are ineligible for MACS payments. MACS maintains a list of these farms and checks all applications for funding against that list. The Act also allows MDA to demand that farms on that list repay MACS funds already disbursed (WQIA §15.20.07.07F), although that option is not currently exercised.[12]

Given its limited budget, the MDA cannot inspect every farm to determine the adequacy of its implementation of a NMP. Therefore, it sends nutrient management specialists to perform a comprehensive on-site inspection of about 10-15 percent of farms every year (MDA 2014). While MDA estimates that roughly 95 percent of farmers are in compliance with the nutrient management planning regulations, an independent estimate based on farmers' self-reports indicates a compliance rate of only 63 percent (Lichtenberg, Parker, and Lane 2010). A likely reason for the discrepancy is MDA's lack of full information about which farms are required to comply with the regulation. MDA's registry of farms consists of operations that have filed for agricultural use assessments for property tax purposes. Since having land that is assessed

[12]Our theoretical analysis assumes that (a) the fine for failure to file a protocol is less than the fine for failure to comply and (b) fines for noncompliance exceed compliance costs. The cumulative nature of the fine for noncompliance with a NMP means that it can easily exceed the fine for failure to file a NMP. The cost of a typical NMP in Maryland is about \$1200 or roughly \$400 a year since a plan is valid for 3 years. Following a plan's recommendations for fertilizer and manure use rarely increases annual nutrient management expenditures and may well reduce them (see for example Lawley, Parker, and Lichtenberg 2009). The combination of formal and informal penalties can thus easily exceed the costs of filing and implementing a NMP.

for agricultural use generates substantial tax savings, farmers have an incentive to obtain agricultural use assessments. But figures from the Census of Agriculture indicate that less than half of the operations classified by the US Department of Agriculture as farms apply for agricultural use assessments. In 2007, for instance, MDA had a total of 6,567 farms in its database of farm operations while the USDA Census of Agriculture listed 12,834.

Farmers who have not applied for agricultural use assessments and know that MDA only inspects farms that have such assessments may still have incentives to comply. Environmental groups with an interest in improving water quality in the Chesapeake Bay have taken farmers to court for supposed violations of nutrient management regulations (Farenthold 2010). People living in residential areas near poultry farms or fields to which manure has been applied may also seek to use violations of nutrient management regulations as a reason for bringing nuisance suits that would be otherwise ruled out by Maryland's right to farm law (Goeringer 2013). Defending lawsuits of these kinds can be quite costly. Being in compliance with an approved nutrient management plan on public record can deter filings of such lawsuits and thus protect farms against incurring legal expenses, giving them an incentive to comply even if they believe that they are not included in MDA's registry of farms. Additionally, for some farms, adoption of NMPs may be optimal even when it is not required by law.

3.5 Data

We examine the implications of enforcement gaps in enforcing Maryland's nutrient management plan regulations using a combination of survey data about individual farm operations, county-level enforcement data from the MDA, and data from the 2007 United States Census of Agriculture. In 2010, the University of Maryland conducted a survey of Maryland farmers' use of best management practices (BMPs), including NMPs, during the year 2009. The survey was administered by the National Agricultural Statistical Service (NASS) of the US Department of Agriculture. A stratified sampling design was used in order to ensure a sufficient number of observations of the high-revenue farm operations that account for the majority of farming activity in Maryland. For computing population estimates, NASS provided a revenue-based expansion factor. The survey was sent to 1,000 farms in the NASS database, which is based on the Census of Agriculture. Of those receiving the survey, 523 responded.[13]

The survey gathered data on the use of 13 different classes of best management practices (BMPs) and on the adoption of NMPs. If the operator used a given BMP, the survey asked whether cost-sharing was received for that BMP. If the operator adopted a NMP, details on the preparation of the plan were collected. NMP preparation details include: (1) if it is primarily phosphorus- or nitrogen-based, (2) the percentage of land it covers, and (3) the type of specialist who prepared the plan. The survey also collected information on several aspects of the farmer's operation including questions on land ownership, farm income and finance, crop operations, and livestock operations. Information about land ownership includes the number of acres the farm operator owned, rented from others, rented to others, and used for free. Information about farm income and finance includes annual sales (measured categorically) and the share of household income obtained from farming. Information about crops includes acreage of land harvested for corn, soybeans, small grains, vegetables, hay, pasture, and other crops. Information about livestock includes the total number of cattle/calves, milk cows, hogs/pigs, poultry, sheep/lamb/goats, and horses present on the operated acres.

[13]There is no reason to believe that the response rate was affected by a desire to avoid revealing information to MDA. The survey is administered by NASS, which has no regulatory role in the implementation of the WQIA, conducts numerous surveys about farming activities every year, and does not share individual-specific data with MDA. Farmers would thus have no reason to believe that their responses would have any regulatory implications. The fact that 23.2 percent of respondents with characteristics indicating that they were required to adopt a nutrient management plan reported not having one provides additional evidence that respondents did not believe that their responses would be used for regulatory purposes.

We use the survey data to construct an indicator variable for being required to have a NMP under the WQIA. The "required" variable is equal to 1 if the farm has cropland and has either eight or more animal units or annual sales of $2,500 or more. The "required" variable is equal to 0 if the farm as no cropland or has cropland but earns less than $2,500 and has fewer than eight animal units. Some respondents with fewer than eight animal units did not report annual sales; we are not able to determine whether those farms are required to have NMPs and therefore exclude them from the analysis. The resulting sample size is 486.

Enforcement data was provided by the MDA for years 2006 through 2010. Due to privacy concerns, the MDA was only able to provide county-level data on enforcement as opposed to farm-level. The enforcement data include the number of farms subject to regulation in each county (by MDA's count), the number of acres required to have a NMP, the number of inspections conducted, the number of warnings issued, and the number and amount of administrative fines levied. We use these data to construct county-level estimates of the probability that a farm is inspected, given that it is known to the MDA. We use enforcement data from 2008, the first year MDA issued fines rather than warnings, i.e., the first year that enforcement was fully in effect.

We use the 2007 Census of Agriculture to determine the total number of farms in a county. The Census of Agriculture provides the total number of farms and the total number of farms with cropland in each county. Since a farm must have cropland in order to use fertilizer, the number of farms with cropland is an upper bound on the number of farms within the purview of the WQIA, as farms may have cropland and use fertilizer but earn less than $2,500 and have fewer than eight animal units, and therefore, be outside of the purview of the WQIA. Table 3.1 presents descriptive statistics weighted to give population estimates. On average, there is a 70.4 percent chance that a farm is included in the MDA registry, suggesting that the enforcement gap is substantial. The probability that MDA inspects a farm included in its registry is about 10 percent.

3.6 Specification and Estimation of the Econometric Model

This section develops an econometric model of a farmer's decision to file a NMP under the presence of enforcement gaps. We assume that the expected net benefit of filing a NMP for farm i in county c, File^*_{ic}, is a function of the probability of being included in MDA's registry of farms, $\tilde{k}_{ic}$

$$\text{File}^*_{ic} = \beta_0 + \beta_1 \tilde{k}_{ic} \times 1[\text{Required}_{ic}] + \mathbf{X_i}\beta_\mathbf{2} + \varepsilon_{ic} \tag{3.1}$$

where $1[\text{Required}_{ic}]$ is an indicator for whether farm i in county c is required to have a NMP under the WQIA, $\mathbf{X_i}$ is a vector of controls, and ε_{ic} is the error term. However, the expected net benefit of filing a NMP for farm i in county c is unobserved; we only observe whether or not a NMP has been filed. Thus, the mapping is as follows:

$$1[\text{File}_{ic}] \begin{cases} 1, & \text{File}^*_{ic} \geq 0 \\ 0, & \text{File}^*_{ic} < 0 \end{cases} \tag{3.2}$$

where File^*_{ic} is an indicator for whether or not a farm has filed a NMP. We assume that $\varepsilon_{ic} \sim N(0, 1)$ and thus estimate the coefficients in equation (3.1) using probit.

Our theoretical model indicates that a farm with a high probability of being included in the MDA farm registry faces a higher expected cost of noncompliance, and hence, we expect the probability of being included in MDA's registry of farms to have a positive effect on the probability of filing a NMP. We proxy for the probability of being included in MDA's registry of farms by dividing the number of farms in county c in MDA's database by the number of farms in county c with cropland in the census. Additionally, farms that have received cost share funds for adoption of conservation practices are assumed to be included in MDA's registry since the overwhelming majority of such spending comes from MDA's Maryland Agricultural Cost Share Program. We therefore adjust the probability of being included in the MDA farm registry to 1 for farms that report having received cost sharing. We use alternate calculations of the probability of being known in our robustness checks, discussed below.

The vector of covariates $\mathbf{X_i}$ includes the total operated acres and indicator variables for various farm operation characteristics including: (1) grain crops (corn, soybean, small grains), (2) hay or pasture, (3) cattle and calves, (4) sheep, lamb, and goats, (5) horses, and (6) annual sales, which are reported categorically. The coefficient on total operated acres captures the economies of scale associated in the adoption of NMPs (McCann 2009). It may also reflect a farmer's perception of being regulated since larger farms interact more with MDA and are also more prominent in the public eye. Accordingly, we expect the coefficient on total operated acres to be positive. Similar considerations suggest that farms with greater annual sales are more likely to believe that NMP regulations apply to them.

There may be benefits to adopting a NMP that are unrelated to the benefits derived from complying with the WQIA. Nutrient management planning is often thought to be win-win, since (in principle at least) it allows farmers to economize on fertilizer purchases while meeting yield goals and reducing runoff simultaneously through such measures as crediting manure nutrients and adjusting fertilizer recommendations for soil fertility status. Farms growing grain crops (corn, soybeans, and/or small grains) and farms raising livestock are most likely to find nutrient management planning profitable and were more likely to have NMPs prior to 1998, when nutrient management planning was voluntary (Lawley, Lichtenberg, and Parker 2009). Since one would expect that the determinants of adoption when NMPs were voluntary would also be determinants of adoption when NMPs are mandatory, we include crop and livestock indicators in our regressions. We expect the coefficients on these variables to be positive.

3.7 Results and Discussion

Table 3.2 reports the marginal effect of the probability of being known to MDA estimated under a variety of specifications. That marginal effect is positive and significantly different from zero in all specifications. Our preferred specification includes the full set of covariates and is reported in column 5 of Table 3.2.

3.7.1 Main Results

Consistent with our theoretical analysis, the marginal effect of the probability of being included in MDA's farm registry is positive and significantly different from zero for farm operations required to have a NMP. It is also economically meaningful: in our preferred specification, a one percentage point increase in the probability of being included in MDA's farm registry is associated, on average, with about a quarter of a percentage point increase in the likelihood of filing a NMP. Since the average probability of having a NMP is 70 percent, this estimate implies that a one percent change in the perceived probability of being regulated is associated with a 17.5 percent increase in the likelihood of having an NMP.

One would expect that commercial scale farms are more likely to file for agricultural use property tax assessments, making them more likely to believe they are included in MDA's enforcement database and thus more likely to file a NMP. One would similarly expect that farm operations that are smaller than commercial scale are less likely to file for agricultural property use tax assessments, suggesting that they are less likely to believe they are subject to nutrient management regulation under the WQIA. Our farm-size specific estimates of the probability of having a NMP and of the marginal effect of being included in the MDA registry, reported in Table 3.3, are consistent with these predictions. The probability of being in compliance with nutrient management regulations (by having a NMP) is increasing in farm size (as measured by revenue category). Compliance rates for very small operations with less than $5,000 in farm sales annually are only on the order of 40-50 percent. Compliance rates are increasing in farm size and noncompliance is virtually non-existent among commercial scale farms: 98-99 percent of farms with annual sales of $40,000 or more report having a NMP.

Our theoretical analysis suggests that the marginal effect of being included in the MDA farm registry decreases with farm size, as large farms are far more likely to have filed for agricultural use assessments, to have ongoing relationships with MDA, and to be more prominent in the public eye. Consistent with this prediction, the marginal effect of being included in the MDA registry is decreasing in farm size. Moreover, for commercial scale farms the marginal effect of a 1 percent increase in the probability of being included in the MDA registry is extremely small (less than a tenth of a percentage point) and not significantly different from zero. Recall that our theoretical analysis indicates that developing a compliance protocol (but not implementing it) is the optimal strategy for a firm whose probability of being known to the regulator is close to 1. In our case, that strategy corresponds to filing a NMP. Our empirical finding is thus consistent with that theoretical prediction.

Maryland has three types of major commercial farm operations: crop farms producing grain crops (corn, soybeans, wheat) primarily for sale to poultry producers; poultry farms, many of which also grow grain; and dairy farms, many of which also grow corn for grain and silage as feed for their animals. One would thus expect MDA enforcement efforts to concentrate on these types of farms. Grain producers use both chemical fertilizers and manure. Poultry and dairy operations produce manure; those with crop operations typically apply that manure to their fields. Consistent with the expectation that these kinds of operations are more likely to be targets of MDA enforcement efforts, we find that estimated compliance is quite high for all three kinds:

between 80 and 90 percent of these types of farms have NMPs (Table 3.3).

Lastly, our theoretical model indicates that warnings provide firms with an incentive to delay the implementation of a compliance protocol, which in our case is the implementation of a NMP, until inspected and warned. Recall that under the WQIA, if a farm fails to implement a NMP by the implementation deadline, then the farm is initially issued a warning with subsequent violations resulting in a fine. We do not have farm-level information about receipt of warnings. However, MDA's county-level data suggest that warnings are effective: warnings were issued in about 38 percent of inspections conducted in 2008 but only 2 percent of subsequent inspections resulted in fines.

3.7.2 Robustness Checks

In order to assess the robustness of our preferred calculation of the probability of being known, we employ two alternative calculations of the probability of being included in the MDA farm registry. The first one is similar to the definition in our preferred specification but does not make the cost-share adjustment; it simply is the number of farms in county c in MDA's database divided by the number of farms in county c with cropland in the census. The second calculation divides the number of farms in county c in MDA's database by the number of farms in county c earning $2,500 or more as reported by the 2007 Census of Agriculture, since nutrient management regulations under the WQIA exempt all farms with less than $2,500 in annual sales.

Table 3.4 presents the marginal effects averaged across all observations under these alternative definitions of the probability of being included in the MDA farm registry. The estimated marginal effects of being included in the MDA farm registry are quite similar to the estimates in Table 3.2.

3.7.3 Implications for Environmental Quality

Our econometric estimates indicate that noncompliance is widespread only among very small farm operations, notably those grossing less than $10,000 in annual sales. As noted earlier, farms of this size are less likely to file for agricultural use property tax assessments and are thus more likely to be overlooked in MDA's regulatory enforcement efforts. These considerations suggest further that enforcement gaps may not have a substantial effect on environmental quality. Such a conclusion would be premature. Some of these operations are likely small horse farms that can generate significant quantities of manure per acre of land, with a correspondingly significant potential for nutrient runoff. Others may engage in small scale vegetable production with substantial intensity of fertilizer use. Even though each farm may be small, the number of farms in the state of these sizes is quite large: the 2007 Census of Agriculture lists 7,242 or 56 percent of all farms in Maryland. Nutrient emissions from all of these small operations combined could thus be substantial.

3.8 Conclusion

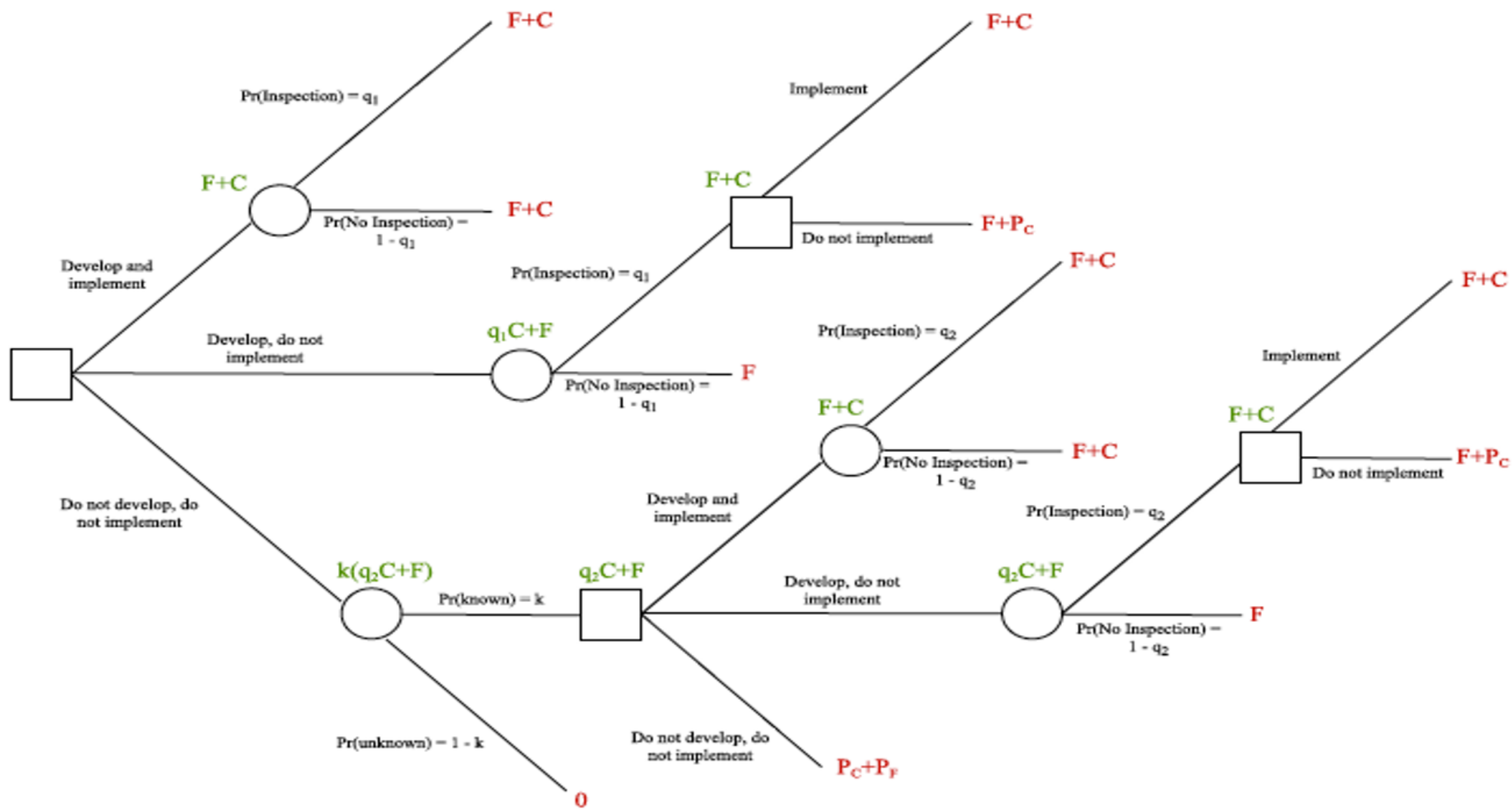
A common assumption in the literature on regulatory compliance is that firms are aware of their regulatory status. This assumption does not always hold; in fact, regulatory agencies frequently lack information about the identities of firms to which regulations apply. If firms believe they are unlikely to be known to the regulator and therefore, unlikely to be subject to enforcement, they are likely to alter their compliance strategies.

We examine theoretically how the optimal compliance strategy of a firm compares to the standard case where regulatory agencies have a complete, up-to-date census of entities subject to regulation. We examine the firm's compliance decision in a setting common to a wide variety of regulations where compliance has two components: the development of an initial compliance structure and the implementation of that compliance structure. In the standard case where firms operate under the assumption of no enforcement gaps, their optimal strategy is to develop an initial compliance protocol but then delay the implementation of that compliance protocol until inspected and warned. However, when the assumption of no enforcement gaps is relaxed, we show that, for sufficiently low values of the probability of being known to the regulator, it is optimal for firms to delay the development of an initial compliance protocol until warned in addition to delaying the implementation of that compliance protocol until inspected and warned.

We then conduct an empirical analysis of the effect of enforcement gaps within the context of the Maryland Water Quality Improvement Act, which requires most farms to file and implement a nutrient management plan. The database used by the Maryland Department of Agriculture in enforcing the NMP requirement consists only of farms that have filed for agricultural use assessments for property tax purposes; that set of farms comprises only about half of the farms in the state. We estimate a probit model of the farmer's decision to file a NMP using farm-level data from a 2010 survey of Maryland farms, county-level enforcement data from the MDA, and county-level data from the 2007 Census of Agriculture. Our estimates indicate that the probability of being included in the MDA's registry of farms subject to regulation has a positive and statistically significant effect on the farm's decision of whether to file a nutrient management plan. The probability of being in compliance with the regulation increases with farm size while the marginal effect of being included in the MDA farm registry declines with respect to farm size; both results are consistent with the predictions of the theoretical analysis.

More broadly, our results suggest that enforcement gaps arising from regulators' lack of current information about the size and composition of a regulated industry can have a significant effect on firms' regulatory compliance strategies and thus on the extent to which regulations achieve their aims. It would thus be useful to know how enforcement gaps affect outcomes such as ambient environmental quality, outbreaks of foodborne illness, protection of patients' health data, quality of care in nursing facilities, and other goals of regulations with structures like that considered here. That information would help regulatory agencies determine whether the return to maintaining up-to-date registries of firms subject to regulation is high enough to justify shifting resources from other enforcement activities to updating registries of regulated entities, i.e., whether the benefits of narrowing enforcement gaps outweigh the costs.

Figure 3.1: Decision Tree for a Firm in the Presence of Enforcement Gaps



The firm's choice is represented by the square nodes while nature's choice is represented by the circular nodes. Payoffs are in red and node payoffs are in green.

Table 3.1: Descriptive Statistics

Variable	Mean	Standard Deviation
Indicator for NMP	0.579	0.0275
Total Operated Acres	255.4	19.39
Number of Animal Units	128.6	27.38
Required under WQIA	0.698	0.0272
1(Corn, Soybean, or Small Grains)	0.433	0.0252
1(Hay or Pasture)	0.616	0.0259
1(Cattle and calves)	0.340	0.0236
1(Sheep, lamb, goats)	0.112	0.0173
1(Horses)	0.246	0.0241
1(Revenue Class 1: $1,000 - 2,499)	0.222	0.0253
1(Revenue Class 2: $2,500 - 4,999)	0.0892	0.0160
1(Revenue Class 3: $5,000 - 9,999)	0.0984	0.0160
1(Revenue Class 4: $10,000 - 19,999)	0.0904	0.0141
1(Revenue Class 5: $20,000 - 39,000)	0.0670	0.0124
1(Revenue Class 6: $40,000 - 99,999)	0.0580	0.0101
1(Revenue Classes 7 & 8: $100,000 - 499,999)	0.153	0.0147
1(Revenue Classes 9 & 10: $500,000 or more)	0.0529	0.00767
Share of County Farms in MDA's Registry)	0.704	0.250
Share of Farms in MDA's Registry Inspected	0.0956	0.0450
Number of Observations	486	

Table 3.2: Marginal Effects from a Probit Model of the Decision to File a NMP

Dependent Variable: 1(File a NMP)	(1)	(2)	(3)	(4)	(5)
Share of County Farms in MDA's Registry x 1[Required]	0.578***	0.474***	0.351***	0.348***	0.249***
	(0.0263)	(0.0519)	(0.0467)	(0.0474)	(0.0524)
Observations	486	486	486	486	486
Crop Indicators	No	No	Yes	Yes	Yes
Livestock Indicators	No	No	No	Yes	Yes
Revenue Indicators	No	No	No	No	Yes

Standard errors in parentheses

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Table 3.3: Average Marginal Effect and Predicted Probability by Revenue Category and Type of Operation

Dep. Var.: 1(File a NMP)	Average Marginal Effect	Average Predicted Probability	N
Panel A: By Revenue Category			
$1,000 - 2,499	0.413***	0.296	62
	(0.092)	(0.025)	
$2,500 - 4,999	0.501***	0.561	32
	(0.112)	(0.031)	
$5,000 - 9,999	0.456***	0.623	37
	(0.102)	(0.034)	
$10,000 - 19,999	0.387***	0.742	41
	(0.102)	(0.029)	
$20,000 - 39,000	0.308***	0.816	32
	(0.092)	(0.030)	
$40,000 - 99,999	0.075	0.971	36
	(0.062)	(0.010)	
$100,000 - 499,999	0.031	0.99	125
	(0.026)	(0.002)	
$500,000 or more	0.059	0.978	59
	(0.047)	(0.007)	
Panel B: By Type of Operation			
Grain Crop	0.194***	0.878	294
	(0.049)	(0.013)	
Cattle	0.274***	0.778	202
	(0.067)	(0.022)	
Poultry	0.165***	0.82	21
	(0.051)	(0.068)	

Standard errors in parentheses.
*** p<0.01, ** p<0.05, * p<0.1

Table 3.4: Marginal Effects using Alternative Definitions of the Probability of Being Known

Dep. Var.: 1(File a NMP)	(1)	(2)	(3)	(4)	(5)
Panel A: Pr(Known) defined as the number of farms in county c divided by the number of farms in county c with cropland:					
Pr(Known) x Required	0.780***	0.593***	0.412***	0.412***	0.263***
	(0.0422)	(0.0790)	(0.0681)	(0.0683)	(0.0746)
Panel B: Pr(Known) defined as the number of farms in county c divided by the number of farms in county c grossing $2,500+:					
Pr(Known) x Required	0.608***	0.469***	0.340***	0.340***	0.240***
	(0.0310)	(0.0582)	(0.0489)	(0.0489)	(0.0551)
Observations	486	486	486	486	486
Total Operated Acres	No	Yes	Yes	Yes	Yes
Crop Indicators	No	No	Yes	Yes	Yes
Livestock Indicators	No	No	No	Yes	Yes
Revenue Indicators	No	No	No	No	Yes

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

4 The Effect of Incomplete Enforcement Information on Ambient Pollution Levels: Evidence from the Clean Water Act

4.1 Introduction

The goal of most environmental regulations is to improve environmental quality. The extent to which this goal is achieved depends on several factors, one of which is the effectiveness of regulatory enforcement. Effective enforcement strategies must provide strong enough incentives to induce firms to comply with the regulation. Economic theory suggests that firms will comply with a regulation only if the expected net benefits of compliance exceed the expected net benefits of noncompliance (Becker 1968). Regulators may alter firms' compliance incentives through the use of enforcement instruments such as self-reporting, inspections, warnings, fines, and criminal sanctions.

Environmental economists typically assume that the regulator and the regulated agents behave under the assumption that the regulator has complete information of the identities of the regulated agents. However, over time, as new firms enter and existing firms exit, the regulator may fail to maintain up-to-date information on the population of active firms. If such information gaps grow over time, firms unknown to the regulator will likely respond by reducing compliance effort. If the regulator's information gaps have a negative effect on a firm's compliance decision, this could lead to aggregate degradation of environmental quality. For a sufficiently large aggregate effect, the benefits to the regulator of acquiring a more complete registry of firms may outweigh the costs of closing these information-induced enforcement gaps.

This paper theoretically and empirically examines how the regulator's incomplete enforcement information of the universe of regulated agents impacts ambient pollution levels. First, I develop a theoretical model of the firm's optimal level of emissions when the probability of being known to the regulator is less than one. I find that a firm's optimal level of emissions is unambiguously decreasing in the probability of being known to the regulator. If decreases in the firm's optimal level of emissions are associated with reductions in ambient pollution levels, then one would expect that ambient pollution levels are also decreasing in the probability of being known to the regulator. This suggests that information gaps may have an effect on a firm's compliance decision and consequently, on ambient pollution levels.

I empirically estimate the effect of information gaps on ambient pollution levels, within the context of Clean Water Act (CWA) permit regulations for various pollutants in the Mississippi River Basin. The CWA requires firms to obtain a permit under the National Pollution Discharge Elimination System (NPDES) prior to discharging into waters of the United States. However, there exist substantial information gaps between the regulator's registry and the universe of firms regulated under the CWA; one study estimated that the universe of regulated firms increased by 45% during a four-year period (USEPA 2005). Using data on the regulator's knowledge of regulated agents from the EPA's Enforcement and Compliance History Online (ECHO) database and data on the universe of regulated agents from the County Business Patterns, I measure the size of this information gap for the 2014-2016 time period. I restrict analysis to firms belonging to the mining and manufacturing sectors as such firms are likely to engage in activities that involve the discharge of pollutants and therefore, likely to belong to the universe of regulated agents.

Then, I construct a catchment/monitoring station-level panel dataset using geospatial data from the National Hydrography Dataset Plus V2 (NHDPlusV2) and pollution data from the Water Quality Portal (WQP). I match the measurement of the size of the information gap to each catchment and estimate a spatial lag model of nitrogen, sulfate, chromium, and phosphorus concentration controlling for upstream delivery of the pollutant, point-source loading of the pollutant, temperature, precipitation, population, inspections as well as catchment, quarter, and year fixed effects. The identifying assumption is that the size of the information gap is not correlated with unobservable, time-variant characteristics that affect ambient pollution levels. In my robustness checks, I conduct placebo tests with other industrial sectors and test the sensitivity to functional form assumptions.

Consistent with my theoretical predictions, I find that an increase in the share of firms included in EPA's registry is associated with a significant and economically meaningful decrease in ambient nitrogen, sulfate, and chromium concentration. Specifically, a one percentage point increase in the share of firms included in the EPA's registry is associated with a 0.49% decrease in nitrogen concentration ($p < 0.01$), a 0.455% decrease in sulfate concentration ($p < 0.10$), and a 0.425% decrease in chromium concentration ($p < 0.10$). For comparison, the mean concentration in my sample for nitrogen, sulfate, and chromium, is 1.463, 150.1, and 0.0378 mg/L, respectively. This implies that increasing the share of firms known to the EPA by just 5 percentage points could lead to measurable reductions in ambient pollution levels. Thus, acquiring information on unknown firms subject to regulation may result in improvements in environmental quality.

This paper primarily contributes to the literature on the enforcement of environmental regulation but also makes contributions to the literature on the economics of water quality. First, regulatory information gaps are not a feature unique to the enforcement setting of the CWA; it is a phenomenon observed in the regulatory settings of the Clean Air Act (CAA), Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA), Resource Conservation and Recovery Act (RCRA), Toxic Substances Control Act (TSCA), Safe Drinking Water Act (SDWA) (USEPA 2005), as well as the Lead-Based Paint Renovation, Repair, and Painting (RRP) Rule (USEPA 2019). Thus, the findings of this paper apply to the broader literature on the enforcement of environmental regulations.

Second, the enforcement literature generally focuses on the effect of various enforcement instruments on compliance and environmental performance. Consistent with economic theory, warnings, inspections, fines, and sanctions have been shown to increase compliance or improve environmental performance (for reviews see; Polinsky and Shavell 2007 and Shimshack 2014). However, these studies implicitly assume complete regulatory information; relaxing this assumption may have implications for both environmental quality and the effectiveness of enforcement instruments. For example, if the regulator fails to update its information on regulated agents, the set of firms that may be chosen for inspection will not reflect the universe of regulated agents. If unknown firms are also more likely to be out of compliance, then regulatory information gaps may have implications for the cost-effectiveness of inspections. There is evidence that these types of enforcement gaps have an effect on compliance; Andarge and Lichtenberg (2019), within the context of nutrient management regulations in Maryland, find that an increase in the probability of being unknown to the regulator has a significant and negative effect on compliance. This paper estimates the effect on ambient pollution levels rather than compliance.

Lastly, this paper contributes to the economics literature on water quality. Most of the studies on water quality come from the literature on nonmarket valuation in which recreational and ecosystem benefits are measured and the literature on drinking water safety, particularly within the context of developing countries (for reviews see Olmstead 2010). There is one study that looks at the effect of regulation on water pollutant concentration; Keiser and Shapiro (2019) find that grants to municipal wastewater treatment plants, which are regulated under CWA permit regulations, reduce water pollutant concentration. This paper is different in that it examines the effect of regulatory information gaps on water pollutant concentration for the mining and manufacturing sectors.

The rest of the paper is organized as follows: section 4.2 reviews the literature, section 4.3 develops a theoretical model, section 4.4 provides background information on the CWA, section 4.5 describes the data and their construction, section 4.6 develops an econometric model of ambient pollutant concentration, section 4.7 presents and discusses the results, and section 4.8 concludes.

4.2 Literature Review

Regulators generally use a variety of enforcement tools to incentivize compliance. However, since regulators have a limited budget and monitoring is costly, they will not monitor every relevant firm every period. Therefore, a firm's compliance decision is a function of its expectations of the regulator's enforcement scheme. A firm will comply with a regulation when the expected benefits of compliance exceed the expected costs. The expected costs of compliance are comprised of direct costs such as the costs associated with the adoption of abatement technology and indirect costs such as reductions in productivity and lost output. The expected benefits include, but are not limited to, the avoidance of fines, future scrutiny from the regulator, and financial impacts from a negative public perception. The regulator may alter some of these costs and benefits; an increase in the probability of an inspection or the magnitude of a fine would, for example, increase the expected benefits of compliance while subsidizing the adoption of abatement technology would decrease the expected costs of compliance.

There is extensive literature on the impact of various enforcement actions and instruments such as inspections, warnings, fines, sanctions, and self-reporting, on both compliance and environmental performance. Generally, one of the first steps in enforcement is an inspection and its estimated effect in the literature is quite mixed. Some studies find that inspections have no effect on compliance (Stafford 2002) or environmental performance (Earnhart 2004b) while others find that inspections increase compliance or improve environmental performance (Telle 2013; 2009; Alberini et al. 2008; Eckert 2004; Dasgupta et al. 2001; Laplante and Rilstone 1996; Gray and Jones 1991; Magat and Viscusi 1990). One study finds that the effect of inspections is contingent on the firm's perception of the effectiveness of enforcement; inspections have no effect on the environmental performance of firms that perceive enforcement as effective but increase the environmental performance of firms that perceive enforcement as ineffective (Earnhart and Friesen 2017).

Following an inspection, the regulator may issue a warning or a fine. Warnings are ubiquitous in the enforcement of environmental regulations; regulators usually issue a warning upon discovering a violation. Theoretical investigations of the role of warnings find that warnings can reduce the probability of switching from a full-compliance equilibrium to a no-compliance equilibrium (Nyborg and Telle 2004) and reduce overcompliance when regulatory errors are present (Rousseau 2009). In some instances, a regulator may issue a fine; several studies find that, consistent with economic theory, an increase in the magnitude of a fine is associated with greater compliance (Earnhart 2004b; Stafford 2002). In fact, the aggregate effect of a fine on compliance rates may be even greater when considering the spillovers it may have on other firms (Shimshack and Ward 2005). This spillover effect may even induce firms already in compliance to over-comply in response to fines levied on other firms (Shimshack and Ward 2008).

Sometimes, when violations are severe or repeated, a regulator may pursue criminal sanctions. Empirical evidence suggests that the possibility of standing trial alone is more of a deterrent than the probability of conviction or the amount of the fine (Almer and Goeschl 2010). Additionally, firms may incur indirect costs in the form of loss of market value as a result of lawsuits (Muoghalu, Robison, and Glascock 1990). Regulators may also require that firms disclose violations or discharge levels to relevant parties; there is evidence that such disclosures have a deterrent effect (Bennear and Olmstead 2008) and improve on-site[14] environmental performance (Khanna, Quimio, and Bojilova 1998).

Most of the literature to date assumes that the regulator and the regulated agents behave under the assumption that the regulator has complete information with respect to the identities of the regulated agents. However, it is not uncommon for the regulator to have incomplete information on the identities of the regulated agents; a study by the United States Environmental Protection Agency's (EPA's) Office of Inspector General (OIG) found substantial gaps in the Office of Enforcement and Compliance Assistance's (OECA) information on entities subject to regulation under several environmental laws, including the Clean Water Act (CWA). Specifically, the study found that, between 2001 and 2005, the size of the regulated universe for the CWA stormwater permits had increased by about 45%. More recently, similar finding was observed for the Lead-Based Paint Renovation, Repair, and Painting (RRP) Rule (USEPA 2019b).

The universe of regulated agents is subject to change over time generating gaps in the regulator's information on the regulated agents. These gaps may potentially have implications for a firm's compliance decision. There is evidence of such an effect; within the context of nutrient management regulations in Maryland, Andarge and Lichtenberg (2019) find that an increase in the probability of being unknown to the regulator has a significant and negative effect on compliance. If the regulator's incomplete enforcement information has an effect on a firm's compliance decision, then it likely also has consequent effects on ambient pollution levels. In the subsequent section, I present a theoretical model of a firm's optimal level of emissions in a setting where the regulator has incomplete information on the universe of regulated agents and discuss its implications for environmental quality. I then test the predictions of the model within the context of the enforcement of CWA permit regulations in the

[14] While on-site toxic releases were reduced in response to loss in market value following disclosure, an increase in off-site transfer of wastes makes the net effect negligible but net risks lower.

Mississippi River Basin.

4.3 Theoretical Framework

This section develops a theoretical model of the firm's optimal level of emissions in a setting where the regulator has incomplete enforcement information on the universe of regulated agents. For simplicity, I assume that there are only two inputs in the production function, $G(x, e)$: emissions, e, and another input denoted by x. The production function is strictly increasing and concave in the level of emissions and the other input with $G_{xe}(x, e) = G_{ex}(x, e)$. Let p denote the output price and w the input price. The firm's optimization problem is

$$\max_{x,e} \ (1-k)\left\{pG(x,e) - wx - a(e_0 - e)\right\} +$$

$$k\left\{q\left[pG(x,e) - wx - a(e_0 - e) - F(e - \bar{L})\right] + (1-q)\left[pG(x,e) - wx - a(e_0 - e)\right]\right\}$$

$$\text{subject to } y \leq G(x,e); e_0 - e \geq 0; e - \bar{L} \geq 0 \tag{4.1}$$

where e_0 is the profit-maximizing level of emissions absent regulation, $a(e_0 - e)$ is the abatement cost function which is strictly decreasing and convex in e with $a(e_0) = 0$, k is the firm's perceived probability that it is known to the regulator, q is the firm's perceived probability of inspection, $\bar{L}$ is the permitted level of emissions, $F(e - \bar{L})$ is the fine incurred by the firm if found to be out of compliance and is strictly increasing and convex in e, and y is the output quantity. Equation (4.1) can be simplified to:

$$\max_{x,e} \ pG(x,e) - wx - a(e_0 - e) - kqF(e - \bar{L}) \tag{4.2}$$

$$\text{subject to } y \leq G(x,e); e_0 - e \geq 0; e - \bar{L} \geq 0$$

Assuming an interior solution, the first-order conditions are:

$$pG_e + a'(e_0 - e) - kqF'(e - \bar{L}) = 0 \tag{4.3}$$

$$pG_x - w = 0 \tag{4.4}$$

By the implicit function theorem,

$$\frac{\partial e^*}{\partial k} = \frac{qF'(e - \bar{L}) \cdot pG_{xx}}{pG_{xx}\left[pG_{ee} - a''(e_0 - e) - kqF''\right] - p^2 G_{xe} G_{ex}} < 0 \tag{4.5}$$

Under the assumptions of the model, the denominator on the right-hand side of equation (4.5) is positive while the numerator is negative. Thus, the firm's optimal level of emissions is unambiguously decreasing in the probability of being known to the regulator.[15] A lower probability of being known decreases the incentive for compliance; when the probability of being known is less than one, the effects of inspections and fines are attenuated and firms have a greater incentive to increase emissions compared to the case when this probability is equal to one. Assuming that decreases in emissions from firms result in decreases in ambient pollution levels, I hypothesize that ambient pollution levels are also decreasing in the probability of being known to the regulator.

4.4 Background

I examine the consequences of the regulator's incomplete information on the universe of regulated agents within the context of Clean Water Act (CWA) permit regulations and their enforcement in the Mississippi River Basin (2-digit HUCs 05, 06, 07, 08, 10, and 11). The CWA was initially passed in 1972 in lieu of the Federal Water

[15]This result would still hold under the assumption that the fine is linearly increasing in the magnitude of the violation ($F" = 0$).

Pollution Control Act in response to growing concerns about water quality (USEPA 2017). Its aim is to "improve or maintain the chemical, physical, and biological integrity of surface waters." Bodies of water considered to be "waters of the United States" fall under the jurisdiction of the CWA (USEPA 2019a).

Under the CWA, any point source discharge into waters of the United States is regarded as unlawful unless a permit, either individual or general, is obtained under the National Pollution Discharge Elimination System (NPDES). Individual permits are issued to specific facilities or persons while several facilities can be covered under a general permit for certain categories of similar discharges (e.g., stormwater discharges). Firms may file a "notice of intent" to discharge under an existing general permit instead of applying for an individual permit. Firms discharging into publicly owned treatment works (POTWs) are not required to obtain a NPDES permit but must meet certain pretreatment criteria. The POTWs themselves, however, must obtain a permit that specifies limits equivalent to or more stringent than the secondary standards for various pollutants (USEPA 2017).

A NPDES permit specifies the effluent limitations that a discharger is required to meet; a firm is considered to be in compliance if its pollutant discharge is at or below the threshold specified in the permit (Copeland 2016). Permits may be issued by the EPA or states with EPA-approved permitting programs, but the EPA ultimately has veto-power. Firms must submit their applications for a permit at least 180 days in advance of discharge (or the expiration of an existing permit). Once an application for a permit is submitted, the permitting agency must notify the public of the draft permit, wait at least 30 days for feedback from the public, and if necessary, grant hearings. Permits are valid for at most five years. Permit holders must test chemical/biological samples and submit discharge monitoring reports (DMRs) containing that information to the state environmental agencies or the EPA.

The primary enforcement agency, the EPA, with the help of state environmental agencies and the Army Corps of Engineers, carries out various enforcement activities. Regulators use enforcements instruments including, but not limited to, reviews of discharge monitoring reports (DMRs), on-site inspections, warnings, assistance to help ensure compliance with permit limits, revocation of permits, penalties, and in severe cases, criminal sanctions. Penalties for negligent violations range from $2,500 - $25,000 per day and/or up to one year in prison with subsequent convictions resulting in fines up to $50,000 per day and/or two years in prison (USEPA 2013). Penalties for knowing violations penalties for knowing violations range from $5,000 - $50,000 per day and/or up to three years in prison with subsequent convictions resulting in fines up to $100,000 per day and/or up to six years in prison. The CWA also allows citizens to sue violating firms directly if: (1) the citizen is harmed by the violation in some way and (2) has given 60 days prior written notice to the violating firm, the state, and the EPA.

If there exist information gaps in the regulator's knowledge of the identities of the regulated firms, the effectiveness of these enforcement instruments may be dampened. Specifically for CWA stormwater permits, the EPA's Office of Inspector General (OIG) found that the size of the regulated universe increased by 45% within a four-year period (USEPA 2005). Yet, the enforcement arm of the EPA relied on an outdated registry of firms to carry out enforcement activities during that same time frame. This type of regulatory information gap may diminish the sting of enforcement which may have consequent implications for ambient pollution levels. In what follows, I first describe the data used to estimate the effect of incomplete enforcement information on ambient pollution levels and their construction. Then, I develop an econometric model of ambient pollution levels under the presence regulatory information gaps.

4.5 Data

I examine the effect of the regulatory information gaps on ambient pollution levels using water quality data from the Water Quality Portal (WQP), EPA facility registration and enforcement data from the Enforcement and Compliance History Online (ECHO) database, data on the universe of regulated agents from the County Business Patterns (CBP), population estimates from the U.S. Census Bureau, temperature and precipitation data from the Global Historical Climatology Network (GHCN), and geospatial data on stream reaches and their associated catchments from the National Hydrography Dataset Plus V2 (NHDPlusV2). I combine these data to construct a stream-reach/catchment-level three year panel dataset. I will first describe each of the data sources and then explain the construction of the final data set.

4.5.1 Description of the Data

Water Quality Data I obtain water quality data for the Mississippi River Basin from the Water Quality Portal (WQP). The Water Quality Portal is a joint service provided by the United States Geological Service (USGS), the EPA, and the National Water Quality Monitoring Council (NWQMC). It includes water quality data from the three main databases—the USGS National Water Information System (NWIS), the EPA STOrage and RETrieval (STORET) Data Warehouse, and the United States Department of Agriculture Agricultural Research Service's (USDA ARS's) Sustaining The Earth's Watersheds – Agricultural Research Database System (STEWARDS). The WQP data contain information on the geographic location of the monitoring station, the date and time of each concentration measurement, the method of measurement, and the value of the measurement.

I obtain data on the concentrations of nitrogen, sulfate, chromium, and phosphorus at various locations in the Mississippi River Basin for years 2014 through 2016. Nitrogen and phosphorus concentration measurements are available for various forms of each pollutant. For example, nitrogen measurements are available for several nitrogen compounds including, but not limited to, inorganic nitrogen (nitrate and nitrite), organic nitrogen, ammonia, ammonium, and Kjeldahl nitrogen.[16] In order to construct a single measure of concentration, the concentration of each chemical compound containing the pollutant of interest was converted to be in terms of the pollutant as follows:

$$\text{conc.} = \frac{\text{atomic mass of pollutant}}{\text{atomic mass of compound}} \times \text{conc. of compound} \tag{4.6}$$

This calculation is not required for the chromium and sulfate concentration data because both pollutants are already reported in units consistent across the entire sample.

A small number of observations have missing values for the geographic coordinates of the station, the measurement date, or both the measurement detection limit and the measurement. Such observations are dropped. Concentration measurements were taken on various days over the course of the study period, January 2014 to December 2016. It appears that there is no regular time interval with which the measurements are taken for the data set as a whole.[17] Figures 4.1, 4.2, 4.3, and 4.4 present a map of the locations of the monitoring stations for nitrogen, sulfate, chromium, and phosphorus, respectively.

EPA Facility and Enforcement Data I obtain data on the facilities known to the EPA from the EPA's Enforcement and Compliance History Online (ECHO) database. ECHO provides facility-level data on location, facility type, industrial classification, enforcement actions, compliance status, pollutant discharge, a publicly owned treatment works (POTW) indicator, and details on the NPDES permit—issue date, effec-

[16] Kjeldahl nitrogen concentration is the total concentration of organic nitrogen and ammonia.
[17] There may be site-specific regularity.

tive date, termination date, and expiration date. Since the study period is January 2014 to December 2016, observations with an issue or effective date past 2016 or a termination date prior to 2014 are dropped.[18] Additionally, since the sectors of interest are mining and manufacturing, for reasons discussed in the succeeding section, I restrict the data to include only observations belonging to Standard Industrial Classification (SIC) codes 10-14 and 20-39. Firms engaging in mining activities that involve the extraction of naturally occurring minerals would fall under SIC codes 10-14. Quarries, well operations, and millers are also included in this category. Manufacturing firms fall under SIC codes 20-39.

County Business Patterns and Census Data I obtain data on the universe of regulated agents from the County Business Patterns (CBP). The CBP data contain county-level figures for the number of facilities classified according to the North American Industrial Classification System (NAICS) for the years 2014 through 2016. Since the sectors of interest are mining and manufacturing, I restrict the data to only include observations belonging to NAICS codes 31-33, which corresponds to the manufacturing sector (SIC 20-39), and NAICS code 21, which corresponds to the mining sector (SIC 10-14). One advantage of restricting the sample to the mining and manufacturing sectors is that there is a one-to-one mapping from the 2-digit SIC code to the 2-digit NAICS code for these sectors. This facilitates comparison between the EPA and CBP data; facilities in the EPA data are mostly classified according to the SIC while facilities in the CBP data are classified according to the NAICS. Lastly, from the U.S. Census Bureau, I obtain county-level estimates of population and the number of housing units.

[18] From conversations with an EPA representative, it appears to be the case that firms are allowed to continue discharging even after a permit has expired, but not after a permit has been terminated.

Global Historical Climatology Network I obtain daily average temperature and total precipitation data for from the Global Historical Climatology Network (GHCN-Daily). The GHCN-Daily database contains daily records from land surface stations for various variables such as minimum temperature, maximum temperature, total precipitation, snowfall, and snow depth along with the geographic coordinates of each station in the network. Since both the GHCN-Daily data and the water quality data are georeferenced, I am able to match each water quality monitoring station with nearby temperature and precipitation stations.

National Hydrography Dataset Plus v2 I acquire geospatial data on waterbodies and their associated catchments from the National Hydrography Dataset Plus v.2 (NHDPlusV2). NHDPlus is a 1:100,000 resolution dataset that incorporates features from the National Hydrography Dataset (NHD), the National Elevation Dataset (NED), and the National Watershed Boundary Dataset (NWBD). The dataset contains information on the characteristics of each NHDFlowline feature (stream reaches). For each NHDFlowline feature, there is a variable that establishes the upstream-downstream relationships in the stream network. Additionally, there is information on the reach length and time of travel of each NHDFlowline feature. The dataset also contains a shapefile of the catchment polygons for each NHDFlowline feature along with the catchment area.

4.5.2 Construction of the Dataset

Redefining NHDFlowline Features The number of NHDFlowline features greatly exceeds the number of monitoring stations; most NHDFlowline features do not have a monitoring station. Therefore, I redefine the stream reach to include every reach between two monitoring stations. The catchment area for this newly defined stream reach then becomes the union of all of the catchments between the two monitoring stations:

$$C_i = \bigcup_{j \in \{i, i-1\}} C_j \tag{4.7}$$

where C_j denotes the catchment of NHDFlowline feature j that is located between the catchments of monitoring station i and monitoring station $i-1$ that is just upstream of i. The corresponding stream reach and catchment characteristics (reach length, time of travel, and catchment area) are calculated as follows:

$$X_i = \sum_{j \in [i, i-1\}} X_j \tag{4.8}$$

where X_j denotes the reach or catchment characteristic of NHDFlowline feature j that is located between monitoring station i and monitoring station $i-1$ that is just upstream of i. Then, I create a new shapefile of catchment polygons with this new definition of reaches and their associated catchments. This newly defined catchment is the unit of observation in my econometric model. Descriptive statistics are presented in Table 4.1. There are four defined catchments; one for each pollutant.

4.6 Econometric Model and Specification

4.6.1 Econometric Model

This section develops an econometric model of ambient pollutant concentration levels under the presence of incomplete enforcement information. The mean of the log of pollutant concentration in stream reach/catchment i in time t, $\ln Conc_{i,t}$, is modeled as follows:

$$\begin{aligned} \ln Conc_{i,t} = \alpha_i + \beta_1 \cdot \text{share known}_{i,y} + \beta_2 \cdot \ln Conc_{i-1,t} + X_{i,t}\beta_3 + \\ \gamma_t + \delta_y + \epsilon_{i,t} \end{aligned} \tag{4.9}$$

where $\ln Conc_{i-1,t}$ is the mean of the log of pollutant concentration at the nearest monitoring location upstream of i at time t, $X_{i,t}$ is a vector of controls, γ_t are time fixed effects, δ_y are year fixed effects, $\epsilon_{i,t}$ is the error term which is assumed to be distributed $N(0, \sigma^2)$, and share $\text{known}_{i,y}$ is the share of firms known to the EPA in year y. Since concentration data are measured at frequencies that are monitoring station-specific, it may be the case that while concentration is recorded for monitoring station i on a given day, it is not recorded for its nearest upstream monitoring station, $i-1$. If it is the case that the upstream neighbor does not have an observation on the same day as the downstream neighbor or vice versa, then that observation would be dropped when estimating equation (4.9) using daily data. To increase the odds that both the upstream and downstream stations in upstream-downstream pairs have concentration measurements available for the given time period, I aggregate the data by taking quarterly means and estimate the following model:

$$\begin{aligned} \ln Conc_{i,qy} = \alpha_i + \beta_1 \cdot \text{share known}_{i,y} + \beta_2 \cdot \ln Conc_{i-1,qy} + X_{i,qy}\beta_3 + \\ \gamma_q + \delta_y + \epsilon_{i,qy} \end{aligned} \tag{4.10}$$

where $\ln Conc_{i,qy}$ is the mean of the log of pollutant concentration in monitoring station i in quarter q in year y, $\ln Conc_{i-1,qy}$ is the mean of the log of pollutant concentration at the nearest monitoring location upstream of i in quarter q in year y, $X_{i,qy}$ is a vector of controls, γ_q are quarter fixed effects, and $\epsilon_{i,qy}$ is the error term which is assumed to be distributed $N(0, \sigma^2)$.

In choosing the level of aggregation, there is a tradeoff between the total number of unique monitoring stations and the total number of observations. As the level of aggregation increases from monthly to quarterly to yearly, the total number of unique monitoring stations increases. This is because the odds that an observation is dropped due to its upstream neighbor not having an observation during that time period decreases with higher levels of aggregation. However, the total number of observations typically decreases due to the aggregation. As a robustness check, models in which the data are aggregated by taking monthly and yearly means are also estimated.

The share of firms in the EPA's registry serves as a proxy for the size of the information gap. It is calculated as follows:

$$\text{share known}_{i,y} = \frac{E_{i,y}}{N_{i,y}} \tag{4.11}$$

where $E_{i,y}$ is the number of firms in the EPA's database in year y and $N_{i,y}$ is the number of firms in the CBP data in year y. The number of firms in the CBP data is measured at the county-level while analysis is conducted at the monitoring-station/catchment-level. Each catchment polygon may not necessarily coincide with or contain a single county polygon; a single catchment polygon generally intersects multiple county polygons. Therefore, I scale this county-level variable to be proportional to the area of the catchment contained within the county and then take the sum across all of the counties intersecting that catchment:

$$N_{i,y} = \sum_{c=1}^{C_i} \frac{\text{Area of } i\text{'s catchment in county } c}{\text{Area of county c}} \cdot N_{c,y} \tag{4.12}$$

$c = 1, ..., C_i$ where C_i is the number of counties intersecting the catchment i. This implicitly assumes that firms are uniformly distributed within a county. Since the EPA data include the geographic coordinates of each facility, I am able to calculate the exact number of facilities in a catchment. However, as this may lead to a share that is greater than 1 in equation (4.11), I aggregate the number of firms in the EPA's database at the county-level and then calculate the corresponding value for the catchment as in equation (4.12).

One potential issue is that not all of the firms in the CBP data are required to obtain a NPDES permit. CBP data include firms that do not discharge pollutants.

Such firms are not required to obtain a NPDES permit and thus would not be included in the EPA's registry. In order to improve the accuracy of my estimate of the share of regulated firms known to the EPA, I restrict the EPA and CBP data to include only firms belonging to the mining and manufacturing sectors. The nature of the activities of firms in these sectors would likely involve the discharge of pollutants and therefore, restricting my analysis to such firms will reduce the measurement error in equation (4.11). Furthermore, recall that firms discharging into publicly owned treatment works (POTWs) are not required to obtain a NPDES permit. Therefore, while the POTW itself would be included in the EPA's registry, the individual firms discharging into the POTW may not be. However, such firms would be included in the CBP data and thus, the share of firms known to the EPA is likely underestimated in equation (4.11).

The share of firms in the EPA's registry serves as a proxy for the size of the information gap with higher shares indicating smaller gaps. The theoretical results suggest that as the probability of being known to the regulator increases, the firm's optimal level of emissions decreases. If increases in the firm emissions lead to increases in ambient pollution levels, then, all else constant, as the share of firms known to EPA increases, the firm's optimal level of emissions and ambient pollution levels decrease. Therefore, I expect the sign of the coefficient on this variable to be negative.

Including pollutant concentration at the nearest monitoring station upstream of i, monitoring station $i-1$, controls for in-stream delivery of pollutants to the downstream station i. One would expect that higher upstream concentrations are associated with higher downstream concentrations due the nature in which water flows and transports pollutants.[19] This suggests that the coefficient on this variable should be positive. The hydrologic literature suggests that the relationship between upstream concentration and downstream concentration may be nonlinear (Yoon, Rhodes, and

[19] If contaminant decay is sufficiently large, then upstream concentration may have no effect on downstream concentration.

Shah 2015). Therefore, I estimate equation (4.10) as log-log model of downstream and upstream pollutant concentration. As a robustness check, I also estimate a linear model of downstream and upstream pollutant concentration.

The vector $X_{i,qy}$ includes point source pollutant loadings, the distance to the upstream monitoring station, the share of facilities inspected within a catchment, temperature, the mean distance from the temperature stations to the water quality monitoring station, precipitation, the mean distance from the precipitation stations to the water quality monitoring station, and the population of the catchment. The weather variables are aggregated by taking quarterly means of measurements taken on days in which concentration is also measured. The kilograms of a pollutant discharged by facilities with a NPDES permit and located within catchment i's is included in the model and serve as a proxy for point-source contributions to pollution. This includes the contributions of POTWs and the firms discharging into POTWs to the pollutant load. While the data do not distinguish between the amounts of each specific pollutant a given facility discharges, it does provide the total discharge from a facility and the pollutants included in that discharge. Thus, this variables is only a proxy for point-source contributions to pollution. Since an increase in the pollutant load into a waterbody increases the pollutant concentration in that waterbody, I expect the coefficient on this variable to be positive. I also include the share of facilities inspected within each catchment. Inspections are thought to deter violations, and therefore, I expect the coefficient on this variable to be negative.

Data on population size are available at the county-level which, as previously discussed, does not necessarily coincide with or is contained within a catchment—a single catchment may contain people from more than one county. Therefore, I scale population size in a manner similar to equation (4.12). Again, this implicitly assumes that people are uniformly distributed within a county. Including population estimates accounts for pollutant contributions from households. As the number of people increases, the amount of human waste also increases. Therefore, all else constant, I expect the coefficient on this variable to be positive for the nitrogen, sulfate, and phosphorus models. I have no a priori expectations for the sign of this coefficient in the chromium model.

Weather patterns may affect pollutant concentrations in several ways. For example, a storm event may result in increased stormwater runoff from urban areas into streams. If the stormwater runoff contains pollutants, then the pollutant concentration in the stream may increase. I include mean of precipitation (in mm) on days in which concentration measurements are taken as a control in equation (4.10) to account for precipitation-related changes in pollutant concentration. Additionally, I include mean of temperature (in tenths of $^\circ$C) to account for any temperature-dependent processes that may affect pollutant concentration. Then, I estimate the equation (4.10) demeaned via OLS and cluster standard errors at the catchment-level.

One potential issue is that the upstream concentration, is endogenous in equation (4.10). When lagged dependent variables are included as a regressor, the within estimator is biased because the error term from the lagged dependent variable is correlated with the mean of the error term in the demeaned version of equation (4.10). Thus, OLS estimates of the coefficient on β_2 will be biased. However, the coefficient on upstream concentration, β_2, is not the parameter of interest. The endogeneity of upstream concentration should not bias OLS estimates of the coefficient on the size of the information gap, β_1, assuming that upstream concentration and the size of the information gap are uncorrelated, conditional on the other regressors (Nickell 1981). This could be violated if the trend in the level of monitoring and enforcement activity is different for different catchments. The inclusion of the share of facilities inspected within a catchment should partly capture such differences. Additionally, the unit of observation is the catchment, not the regulatory jurisdiction. Therefore, changes in monitoring and enforcement activity are likely not occurring at the catchment level as catchments may intersect multiple regulatory jurisdictions.

4.6.2 Industrial Sectors and Pollutants

I investigate the effect of incomplete enforcement information on the mining and manufacturing sectors on the pollutant concentrations of nitrogen, chromium, sulfate, and phosphorus. Recall, that I restrict analysis to the mining and manufacturing sectors. The selection of these two industries is to facilitate comparison across data sources and reduce measurement error in the share of firms known to EPA. Data from the ECHO database largely report the SIC codes of facilities while data from the CBP report the NAICS codes. There is a one-to-one correspondence between the two-digit SIC and the two-digit NAICS codes for the mining and manufacturing sectors which facilitates comparison between the two data sources. Additionally, firms in these two sectors are likely to engage in activities that involve the discharge of pollutants and therefore, more likely to belong to the universe of regulated agents under the CWA.

Nitrogen comes from various point and nonpoint sources. The major nonpoint source contributor is agriculture, which is not regulated under CWA *permit* regulations. The manufacturing sector, however, also emits nitrogen as part of the production process. For example, wastewater discharged from pulp and paper mills may contain nitrogen and may contribute to eutrophication. This is particularly important for the Gulf of Mexico, where the Mississippi River Basin drains into, since nitrogen is the limiting nutrient and has led to a large hypoxic zone (NOAA 2019). Phosphorus also plays a role in the formation of the hypoxic zone in the Gulf of Mexico. Similar to nitrogen, nonpoint source pollution from agriculture is one of the primary sources of phosphorus pollution. However, industrial processes such as steel production, metal finishing, food and beverage processing, and industrial cleaning also contribute to phosphorus pollution. It is also the limiting nutrient in freshwater ecosystems; my sample consists of freshwater streams. For these reasons, I estimate models of nitrogen and phosphorus concentration.

Both the mining and manufacturing sectors discharge chromium; metal ore mining, electroplating, leather tanning, and textile manufacturing are a few examples of activities within these two sectors that likely involve the discharge of chromium. Chromium pollution mostly comes from point sources, unlike nitrogen and phosphorus. Thus, the estimation of the chromium serves as a robustness check since it is a model that is unlikely to be confounded by time-varying nonpoint source contributions. Lastly, I estimate a model of sulfate concentration. Sulfate, in water, is relatively harmless both for human and environmental health. Industrial sources of sulfate include, but are not limited to, mines, smelters from pulp and paper mills, and textile mills and tanneries (WHO 2004). Atmospheric deposition is the major nonpoint source of sulfate in surface water. This is partially controlled for by the inclusion of weather variables.

4.7 Results and Discussion

The universe of regulated agents may evolve over time; new firms may enter and existing firms may exit the industry. If the regulator's registry is not updated frequently enough to reflect this evolution, then regulatory information gaps will be generated. Additionally, existing firms already unknown to the regulator will remain unknown. Such information gaps may dampen the effects of enforcement instruments and have implications for a firm's compliance decision which in turn may have an effect on ambient pollution levels. In this section, I present and discuss the effect of regulatory information gaps on ambient pollutant concentration within the context of CWA permit regulations. Table 4.2 presents estimates of the coefficients of interest from equation (4.10). Most of the estimated coefficients for the control variables have the expected sign.

4.7.1 The Effect of Incomplete Enforcement Information on Ambient Pollution Levels

The theoretical model predicts that an increase in the share of firms known to the regulator results in a decrease in ambient pollution levels. Consistent with this prediction, the results indicate that increases in the share of firms known to the EPA result in decreases in nitrogen, sulfate, and chromium concentration but not phosphorus concentration. The results indicate that a one percentage point increase in the share of firms included in the EPA's registry results in a 0.49% decrease in nitrogen concentration ($p < 0.001$), a 0.46% decrease in sulfate concentration ($p < 0.10$), and a 0.43% decrease in chromium concentration ($p < 0.10$). For comparison the mean concentration in my sample for nitrogen, sulfate, and chromium, is 1.46, 150.0, and 0.0378 mg/L, respectively. Increasing the share of firms known to the EPA by just 5 percentage points could lead to measurable reductions in ambient pollution levels. Thus, acquiring information on unknown firms subject to regulation may result in improvements in environmental quality.

The EPA's ambient water quality criteria specify the maximum concentration of a toxic pollutant in water that will not pose a significant risk to most aquatic species. There are two ambient water quality measures: Criterion Maximum Concentration (CMC) and Criterion Continuous Concentration (CCC). The CMC is 0.57 mg/L for chromium III and 0.016 mg/L for chromium IV. The mean concentration for total chromium (chromium III and chromium IV) in my sample is 0.0378 mg/L. Unfortunately, the data do not distinguish between the two forms of chromium. Regardless, the mean concentration is below the CMC for chromium III and above the CMC for chromium IV. I estimate that a 5 percentage point increase in the share of facilities known to EPA results in a 2.15% decrease in chromium concentration. A 2.15% decrease in the mean concentration amounts to approximately 0.000813 mg/L, which is small relative to the CMC. However, the sample is restricted to the mining and manufacturing sectors. An improvement in information across all chromium discharging industries may yield larger effects. A similar exercise is not able to be carried out for sulfate because, to my knowledge, there are no ambient water quality standards for sulfate in streams and rivers.

The EPA does have recommendations for ambient nutrient levels. However, these are region-specific parameters. For the Mississippi River Basin, the mean recommended ambient nitrogen concentration is 0.52 mg/L. A five percentage point increase in the share of facilities known to EPA results in a 2.45% decrease in ambient nitrogen concentration. A 2.45% reduction in nitrogen concentration from the mean concentration in my sample is about 0.03577 mg/L. This appears to be a relatively small effect in absolute terms. However, relative to the overall contribution of mining and manufacturing point sources to nitrogen pollution, this effect is not as small as it appears. Additionally, the average nitrogen concentration in my sample is 1.463 mg/L which is three times the recommended level. Thus, reducing the size of the information gap could bring ambient levels closer to the recommended levels. Given that the nutrient runoff from the Mississippi River Basin substantially contributes to hypoxia in the Gulf of Mexico, reducing these information gaps may lead to benefits in terms of improved water quality in the Gulf of Mexico. 4.7.2 discusses this in greater detail.

If enforcement gaps have a large enough effect on ambient pollution levels, then it is more likely that the benefits of acquiring information to update the registry of regulated agents outweigh the costs. An exercise comparing the returns to various enforcement instruments to the returns of acquiring information on the regulated universe would allow for the determination of the optimal resource allocation between enforcement strategies. However, the literature largely measures the effect of enforcement instruments on the binary decision to comply or the environmental performance of a firm, not ambient pollution levels, making comparison difficult. Future research on the effect of conventional enforcement instruments on ambient pollution levels would allow for the determination of the optimal allocation of resources.

4.7.2 The Benefits of Acquiring Information

The benefits of closing regulatory information gaps, in terms of improved water quality, depend on the value of improved water quality. As the Mississippi River discharges into the Gulf of Mexico, water quality improvements in the Mississippi River Basin are valued by impacted households within the watershed and households that value the health of the Gulf. A representative nationwide survey of U.S. households was conducted by Stefanski and Shimshack (2016) to estimate the willingness to pay for improved water quality in the Gulf of Mexico through an expansion in the Flower Garden Banks National Marine Sanctuary; households are willing to pay between \$35 and \$107 per year for this expansion. Hayes, Kling, and Lawrence (2016) argue that even though Stefanksi and Shimshack (2016) consider a specific water quality improvement, it may still provide a general measure of the value of improved environmental quality in the Gulf of Mexico.

Assume that (1) a 41% reduction in nitrogen load and a 29% reduction in phosphorus load achieves 59% of the water quality improvement in the Gulf of Mexico as the marine sanctuary expansion would[20], (2) a 41% reduction in nitrogen load is equivalent to a 41% reduction in nitrogen concentration, and (3) households only care about the improvement in water quality, not the manner in which it was achieved. The estimates from column (1) in Table 4.2 suggest that a 5 percentage point increase in the share of firms known to the regulator results in a 2.45 percent decrease in nitrogen concentration. Using the smallest WTP estimate from Stefanski and Shimshack

[20]Hayes, Kling, and Lawrence (2016) argue that such a reduction in Iowa would result in 15% of the improvement achieved by the marine sanctuary expansion. However, since 80% to 90% of freshwater discharge into the Gulf of Mexico is from the Mississippi River system and 74% of the pollution comes from land, I argue that such a reduction in the Mississippi River Basin would achieve, at least, 59% of the water quality improvement achieved by the marine sanctuary expansion. This is likely an extremely conservative estimate.

(2016), this suggests that the benefits of the improvement in water quality from a 5 percentage point increase in the share of firms known to the regulator is about $165.9 million per year in 2020 dollars.[21] Note, this is a conservative estimate because it does not include the benefits of improved water quality in streams within the Mississippi River Basin.

4.7.3 Robustness Checks

To assess the robustness of the estimates of the effect of incomplete enforcement on ambient pollution levels, I conduct placebo tests and estimate the model in equation (4.9) at monthly and yearly aggregations. Since chromium is a specific pollutant, I can identify industrial sectors whose activities do not involve the discharge of chromium. The size of the information gap for such an industry should have no effect on chromium concentration. The activities of facilities in the Water Utilities sector, corresponding to NAICS 2213, should not involve the discharge of chromium. Similarly, activities within the Agriculture, Forestry, Fishing, and Hunting sector, corresponding to NAICS 11, likely do not involve the discharge of chromium. Using the size of the information gap for these two sectors, I estimate the model in equation (4.10) for chromium. The results are presented in Table 4.3. It is reassuring that the size of the information gap in these two sectors has no significant effect on chromium concentration.

As a second robustness check, I aggregate the data by taking monthly and yearly means rather than quarterly. Recall that in moving to higher levels of aggregation (i.e., from monthly to quarterly to yearly), there is a tradeoff between total number of observations and total number of monitoring stations. With monthly aggregations, the total number of observations is higher while the total number of monitoring stations is lower relative to yearly aggregations. To assess whether the results are

[21] Assuming that there are about 125.82 million households in the United States.

sensitive to the level of aggregation, I estimate equation (4.9) after taking monthly and yearly means of the relevant variables. The results are reported in Tables A.1 and A.2 and are largely consistent with the results from the quarterly aggregation of the data.

Lastly, I estimate models in which the relationship between upstream and downstream concentration is linear. The results of these regressions are presented in column (2) of Table 4.4. The point estimates have the same sign as the estimates from the preferred specification. However, the hydrologic literature suggests that the relationship between upstream and downstream concentration is logarithmic. Thus, there is a theoretical basis for a log-log specification. Plots of upstream concentration vs. downstream concentration and the log of upstream concentration vs. the log of downstream concentration confirm a logarithmic relationship.

4.7.4 The Effect of Inspections on Ambient Pollution Levels

Economic theory suggests that increases in the magnitude of the probability of being inspected increase a firm's expected cost of noncompliance and thereby, decreases the likelihood that a firm will choose to comply with the regulation. If more firms comply with the regulation, then, all else constant, ambient pollution levels will decrease. The point estimate on the share of facilities inspected is negative in all of the specifications, implying that increases in the magnitude of the probability of inspection are associated with improvements in water quality. However, this result is not significantly different from zero at any conventional significance level.

In the literature, the effect of inspections on compliance or environmental performance is mixed. Similar to this study, Earnhart (2004) and Stafford (2002) both find that inspections have no effect on compliance or environmental performance. Within the context of wastewater discharges by municipal wastewater treatment plants in Kansas, Earnhart (2004) finds that while federal inspections have a deterrent effect, state inspections do not. The data used in this study do not distinguish between state and federal inspections and therefore, I cannot disentangle the two effects. However, since the EPA delegates inspection responsibilities to the states, it is likely that a substantial number of the inspections are conducted by the states. Similarly, Stafford (2002) finds that past inspections do not deter future violations for hazardous waste regulations.

Other studies, however, find that inspections indeed have a deterrent effect. Inspections are found to reduce TSS and BOD discharges (Dasgupta et al. 2001) and increase compliance with air pollution regulations (Gray and Deily 1996). One study finds that while inspections do significantly deter future violations, the magnitude of their effect is quite small (Eckert 2004). These mixed results could be due to industry- or regulation-specific differences in the effectiveness of inspections or the manner in which the inspection variable is estimated in my model.

4.8 Conclusion

A common assumption in the literature is that the regulator has complete information on the universe of regulated agents. However, this assumption rarely holds in regulatory environments; substantial informational gaps are observed in the regulatory environments of several major environmental regulations. Such information gaps may affect a firm's compliance decision and therefore have consequent effects on ambient pollution levels. I examine theoretically how a firm's optimal level of emissions changes with respect to the likelihood of being included in the regulator's registry of regulated agents. I find that the optimal level of emissions is unambiguously decreasing in the probability of being known to the regulator.

Then, I empirically investigate the effect of the regulator's information gaps on ambient nitrogen, sulfate, chromium, and phosphorus concentration within the context of the enforcement of Clean Water Act (CWA) permit regulations on the manufacturing and mining industries in the Mississippi River Basin. Consistent with the theoretical prediction, the results indicate that an increase in the share of facilities included in the EPA's registry has a negative and statistically significant effect on ambient nitrogen, sulfate, and chromium concentrations. Thus, it is possible that improvements in the EPA's information on the identities of the regulated agents may improve water quality. Back of the envelope calculations of the benefits of acquiring information suggest that a 5 percentage point increase in the share of known nitrogen-polluting firms leads to benefits, in terms of improved water quality in the Gulf of Mexico, of $165.9 million per year.

Figure 4.1: Nitrogen Monitoring Stations in the Mississippi River Basin

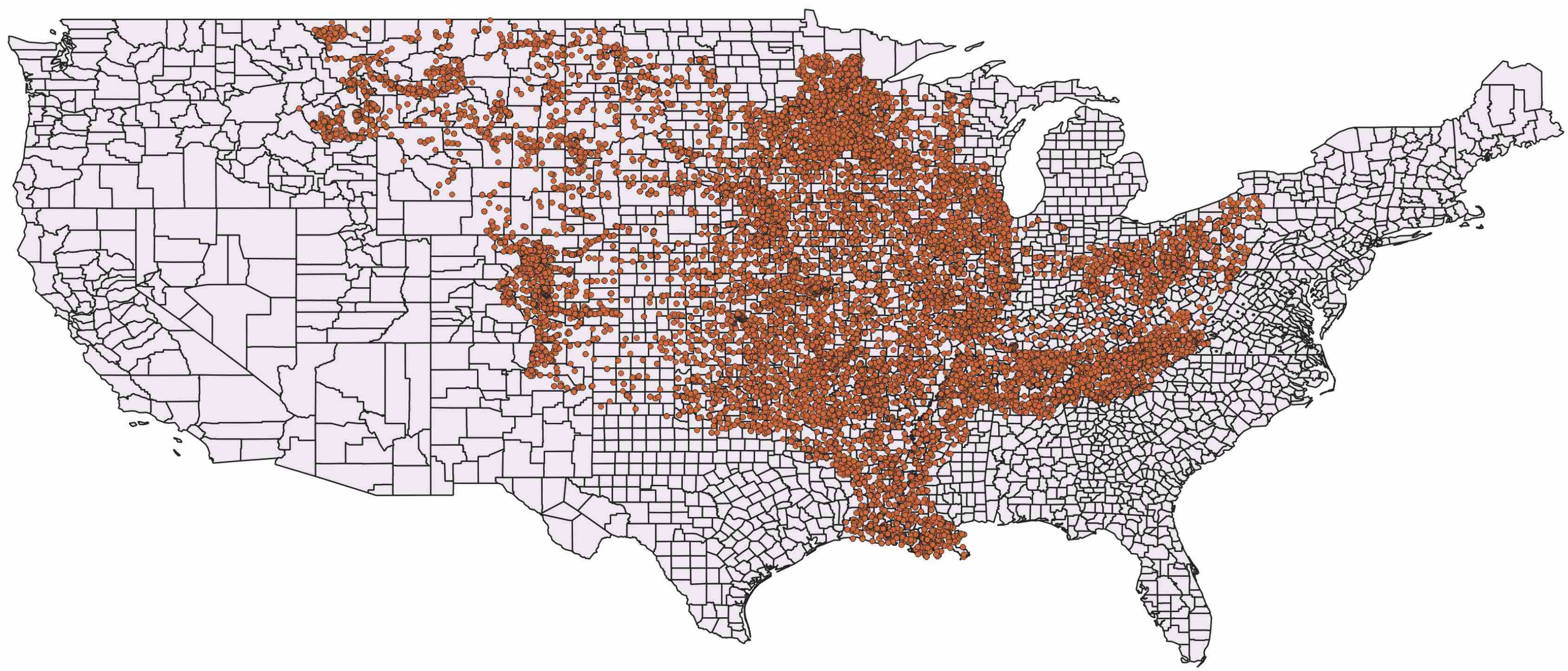


Figure 4.2: Sulfate Monitoring Stations in the Mississippi River Basin

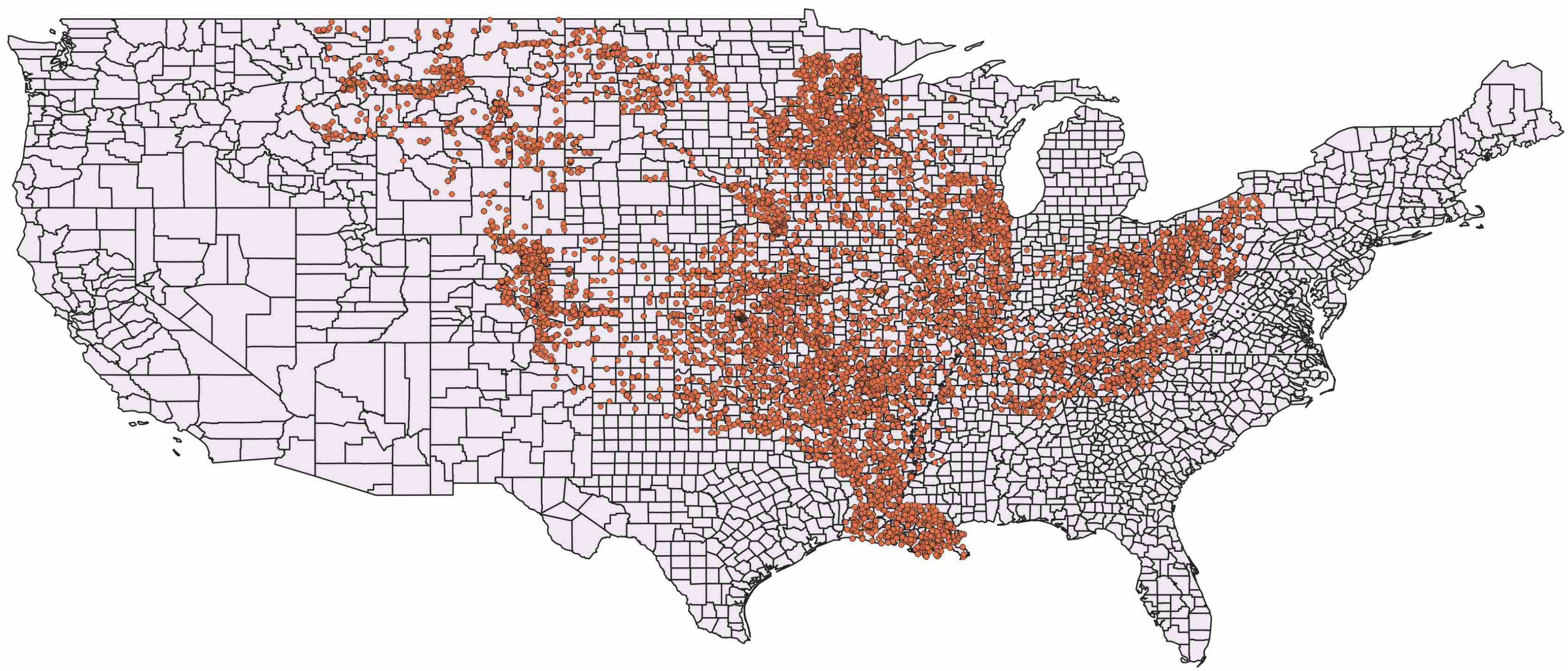


Figure 4.3: Chromium Monitoring Stations in the Mississippi River Basin

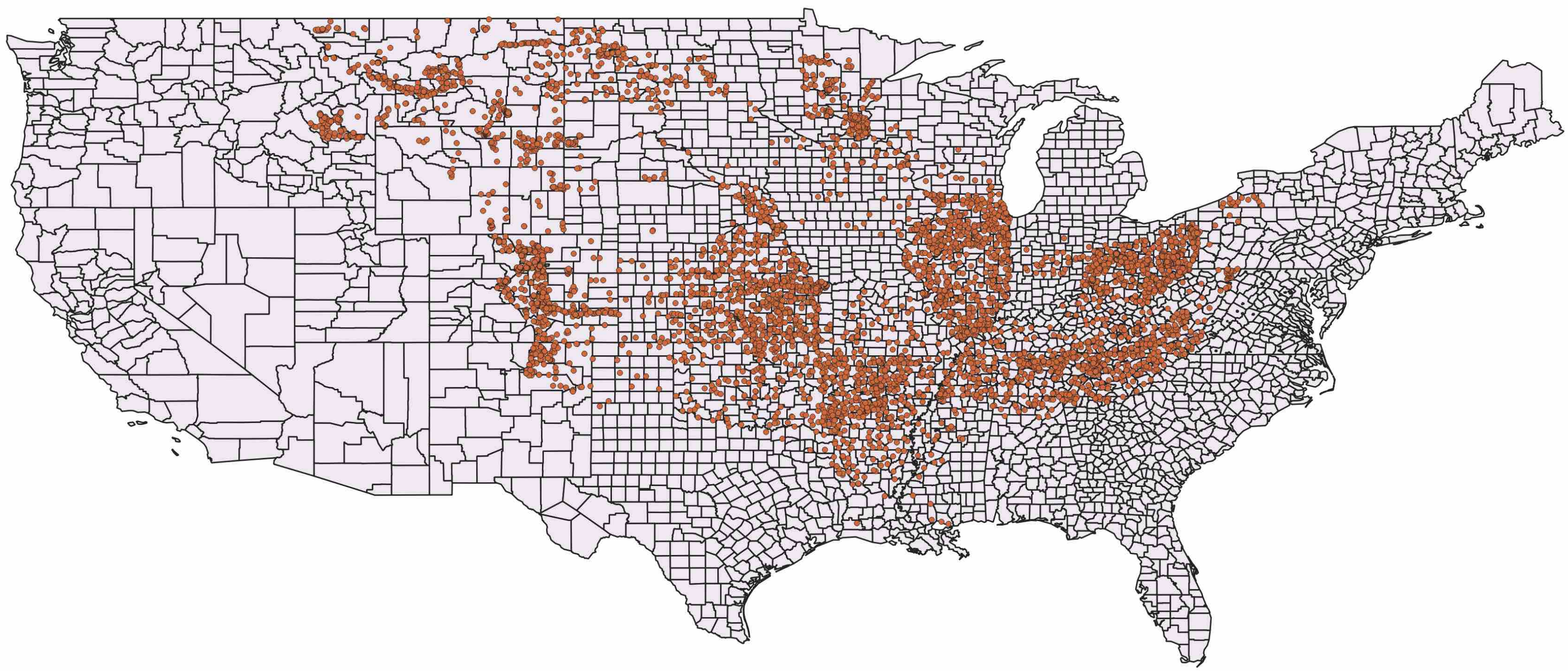


Figure 4.4: Phosphorus Monitoring Stations in the Mississippi River Basin

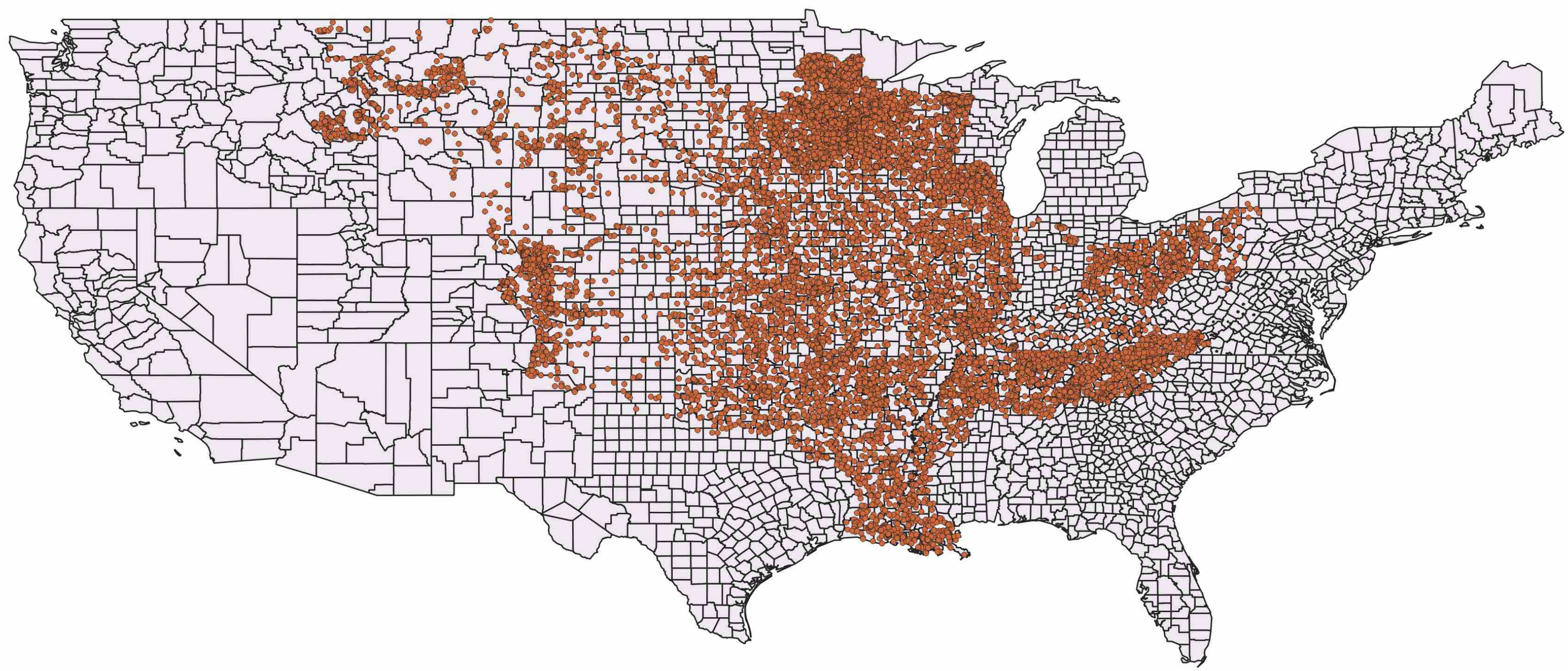


Table 4.1: Descriptive Statistics

Variables	(1) Nitrogen	(2) Sulfate	(3) Chromium	(4) Phosphorus
Water Quality:				
Pollutant conc. (mg/L)	1.463	150.0	0.0378	0.8616
Enforcement:				
Share of facilities known to EPA	0.166	0.180	0.131	0.148
Share known to EPA (NAICS 2213)	-	-	0.816	-
Share known to EPA (NAICS 11)	-	-	0.254	-
Share of facilities inspected	0.0287	0.0308	0.0310	0.0269
Weather:				
Daily avg. temp. (tenths of $^\circ$C)	158.0	157.7	164.8	164.2
Distance to temp. station (km)	180.6	182.6	188.3	179.8
Daily precip. (mm)	29.56	29.84	36.58	36.58
Distance to precip. station (km)	24.76	25.39	21.61	25.91
Reach/Catchment:				
Point source loading (kg)	494,588	591,183	563,070	452,331
Population	8,266	10,184	18,155	6,194
Length (km)	292.1	326.8	487.4	201.2
Area (sq km)	444.6	490.4	723.8	300.0
N	11,217	11,021	1,567	21,906

Table 4.2: Estimates of the effect of incomplete enforcement information on ambient pollution levels

	(1)	(2)	(3)	(4)
Dependent variable:	Ln(Nitrogen conc.)	Ln(Sulfate conc.)	Ln(Chromium conc.)	Ln(Phosphorus conc.)
Share of facilities known	-0.490***	-0.455*	-0.425*	-0.0637
	(0.123)	(0.251)	(0.251)	(0.184)
Ln(Upstream conc. (mg/L))	0.0731***	0.241***	0.388***	0.102***
	(0.0142)	(0.0606)	(0.104)	(0.0173)
Share of facilities inspected	-0.0260	-0.0748	-0.313	-0.0130
	(0.280)	(0.119)	(0.398)	(0.127)
Point source loading (kg)	-5.75e-09	2.74e-09	-1.99e-08	0
	(4.90e-09)	(4.03e-09)	(1.52e-08)	(1.57e-10)
Temperature (tenths $^\circ$C)	0.000237	-0.000166	0.000288	0.000495***
	(0.000148)	(0.000114)	(0.000462)	(0.000160)
Precipitation (mm)	0.000474***	-0.000543***	0.00242***	0.00140***
	(0.000126)	(0.000105)	(0.000419)	(9.83e-05)
Population	-8.82e-05*	-1.81e-05	-9.23e-05	-9.76e-05
	(4.79e-05)	(5.26e-05)	(0.000141)	(7.24e-05)
N	11,217	11,021	1,567	21,906
Number of catchments	4,742	3,997	792	8,606
Controls	Yes	Yes	Yes	Yes
Catchment FE	Yes	Yes	Yes	Yes
Quarter FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Mean of Conc.	1.463	150.0	0.0378	0.616

Standard errors clustered at the catchment level in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 4.3: Placebo tests using NAICS 2213 and NAICS 11

Ln(Chromium conc. (mg/L))	(1) Water Utilities (NAICS 2213)	(2) Agriculture, Forestry Fishing, and Hunting (NAICS 11)
Share of facilities known to EPA	-0.242	-0.133
	(0.323)	(0.419)
Ln(Upstream chromium conc.)	0.388***	0.387***
	(0.105)	(0.105)
Observations	1,567	1,567
Number of catchments	792	792
Catchment FE	Yes	Yes
Quarter FE	Yes	Yes
Year FE	Yes	Yes

Standard errors clustered at the catchment level in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 4.4: Estimates of the effect of incomplete enforcement information with a linear relationship between upstream and downstream concentration

Dependent var.: Concentration (mg/L)	(1) Preferred Specification	(2) Linear Model
Nitrogen:		
Share of facilities known to EPA	-0.490***	-0.600*
	(0.123)	(0.315)
Upstream nitrogen conc. (mg/L)	0.0731***	-0.619
	(0.0142)	(0.616)
Share of facilities inspected	-0.0260	-1.35e-08
	(0.280)	(9.38e-09)
Sulfate:		
Share of facilities known to EPA	-0.455*	-69.37***
	(0.251)	(26.32)
Upstream sulfate conc. (mg/L)	0.241***	-43.04
	(0.0606)	(28.75)
Share of facilities inspected	-0.0748	-7.99e-08***
	(0.119)	(2.87e-08)
Chromium:		
Share of facilities known to EPA	-0.425*	-0.0343***
	(0.251)	(0.0117)
Upstream chromium conc. (mg/L)	0.388***	-0.0443
	(0.104)	(0.0288)
Share of facilities inspected	-0.313	-1.68e-10
	(0.398)	(6.07e-10)
Phosphorus:		
Share of facilities known to EPA	-0.0637	-1.030
	(0.184)	(1.443)
Upstream phosphorus conc. (mg/L)	0.102***	-1.055
	(0.0173)	(0.704)
Share of facilities inspected	-0.0130	4.13e-10
	(0.127)	(3.03e-10)
Controls	Yes	Yes
Catchment FE	Yes	Yes
Quarter FE	Yes	Yes
Year FE	Yes	Yes

Standard errors clustered at the catchment level in parentheses
*** $p<0.01$, ** $p<0.05$, * $p<0.1$

A Appendix

A.1 Robustness Check: Aggregating data to the monthly level

Table A.1: Estimates of the effect of incomplete enforcement information on ambient pollution levels using data aggregated to the monthly level

	(1)	(2)	(3)	(4)
Dependent variable:	Ln(Nitrogen conc.)	Ln(Sulfate conc.)	Ln(Chromium conc.)	Ln(Phosphorus conc.)
Share of facilities known	-0.453***	-0.688	-0.208	-0.0635
	(0.127)	(0.451)	(0.224)	(0.255)
Ln(Upstream conc. (mg/L))	0.119***	0.281***	0.341***	0.103***
	(0.0173)	(0.0748)	(0.0929)	(0.0114)
Share of facilities inspected	-0.114	0.0315	-0.0391	-0.0220
	(0.239)	(0.115)	(0.356)	(0.120)
Point source loading (kg)	-5.42e-10	3.33e-09	2.27e-07**	1.15e-10
	(5.44e-09)	(5.30e-09)	(1.09e-07)	(9.07e-11)
Temperature (tenths $^\circ$C)	-4.70e-05	-5.06e-05	-0.000471	0.000316**
	(0.000161)	(0.000126)	(0.000484)	(0.000135)
Precipitation (mm)	0.000206*	-0.000624***	0.00189***	0.00130***
	(0.000105)	(8.44e-05)	(0.000382)	(7.00e-05)
Population	-0.000127**	1.28e-05	3.23e-05	-0.000191**
	(6.16e-05)	(3.76e-05)	(0.000206)	(8.03e-05)
N	12,163	12,872	1,412	30,667
Number of catchments	3,902	3,287	586	7,678
Controls	Yes	Yes	Yes	Yes
Catchment FE	Yes	Yes	Yes	Yes
Month FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Mean of Conc.	1.467	129.3	0.0527	0.682

Standard errors clustered at the catchment level in parentheses
*** p<0.01, ** p<0.05, * p<0.1

A.2 Robustness Check: Aggregating data to the yearly level

Table A.2: Estimates of the effect of incomplete enforcement information on ambient pollution levels using data aggregated to the yearly level

	(1)	(2)	(3)	(4)
Dependent variable:	Ln(Nitrogen conc.)	Ln(Sulfate conc.)	Ln(Chromium conc.)	Ln(Phosphorus conc.)
Share of facilities known	-0.362***	-0.435**	-0.461*	0.0515
	(0.128)	(0.211)	(0.249)	(0.157)
Ln(Upstream conc. (mg/L))	0.0656***	0.193***	0.456***	0.105**
	(0.0187)	(0.0729)	(0.150)	(0.0446)
Share of facilities inspected	0.0528	-0.123	-0.671	-0.0659
	(0.277)	(0.113)	(0.470)	(0.115)
Point source loading (kg)	-9.71e-09	7.71e-10	-4.97e-09	8.26e-11
	(6.11e-09)	(4.00e-09)	(1.84e-08)	(1.25e-10)
Temperature (tenths $^\circ$C)	-0.000143	-0.000747**	-0.000399	0.000394
	(0.000238)	(0.000377)	(0.00165)	(0.000284)
Precipitation (mm)	0.000352	-0.000331*	0.00172**	0.000849***
	(0.000220)	(0.000187)	(0.000748)	(0.000225)
Population	-0.000110***	-7.63e-06	-0.000181	-7.40e-05
	(4.16e-05)	(5.00e-05)	(0.000112)	(5.24e-05)
N	7,794	6,400	1,281	13,141
Number of catchments	5,727	4,652	1,002	9,555
Controls	Yes	Yes	Yes	Yes
Catchment FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Mean of Conc.	1.549	168.2	0.146	0.602

Standard errors clustered at the catchment level in parentheses
*** p<0.01, ** p<0.05, * p<0.1

References

[1] Alberini, Anna, and David H. Austin. 1999. "Strict Liability as a Deterrent in Toxic Waste Management: Empirical Evidence from Accident and Spill Data." *Journal of Environmental Economics and Management* 38(1):20–48.

[2] Alberini, Anna, Erik Lichtenberg, Dominic Mancini, and Gregmar I. Galinato. (2008). "Was It Something I Ate? Implementation of the FDA Seafood HACCP Program." *American Journal of Agricultural Economics* 90 (1): 28–41. https://doi.org/10.1111/j.1467-8276.2007.01038.x.

[3] Almer, C., and T. Goeschl. (2010(. "Environmental Crime and Punishment: Empirical Evidence from the German Penal Code." *Land Economics* 86 (4): 707–26. https://doi.org/10.3368/le.86.4.707.

[4] Becker, Gary S. (1968). "Crime and Punishment: An Economic Approach." *Journal of Political Economy* 76 (2): 169–217.

[5] Bennear, Lori S., and Sheila M. Olmstead. (2008(. "The Impacts of the 'Right to Know': Information Disclosure and the Violation of Drinking Water Standards." *Journal of Environmental Economics and Management* 56 (2): 117–30. https://doi.org/10.1016/j.jeem.2008.03.002.

[6] Blundell, Wesley. (2020). "When Threats Become Credible: A Natural Experiment of Environmental Enforcement from Florida." *Journal of Environmental Economics and Management* 101:102288.

[7] Blundell, Wesley, Gautam Gowrisankaran, and Ashley Langer. (2018). "Escalation of Scrutiny: The Gains from Dynamic Enforcement of Environmental Regulations." 24810 in. Cambridge, MA: National Bureau of Economic Research.

[8] Bureau of Labor Statistics. Establishment age and survival statistics, https://www.bls.gov/bdm/bdmage.htm#AG, accessed August 9, 2019.

[9] Chesapeake Bay Foundations (CBF). (2017). The history of Chesapeake Bay cleanup efforts. Retrieved from http://www.cbf.org/how-we-save-the-bay/chesapeake-clean-water-blueprint/the-history-of-bay-cleanup-efforts.html

[10] Chislock, M. F., Doster, E., Zitomer, R. A. & Wilson, A. E. (2013). Eutrophication: Causes, Consequences, and Controls in Aquatic Ecosystems. *Nature Education Knowledge*, 4(4), 10.

[11] Cohen, M. (1999). Monitoring and enforcement of environmental policy. *International Yearbook of Environmental and Resource Economics*, 3, 44-106.

[12] Copeland, Claudia. (2016). "Clean Water Act: A Summary of the Law." Congressional Research Service, Library of Congress.

[13] Dasgupta, Susmita, Benoit Laplante, Nlandu Mamingi, and Hua Wang. (2001). "Inspections, Pollution Prices, and Environmental Performance: Evidence from China." *Ecological Economics*, 12.

[14] Deutsch, W. (2017). Surprising numbers behind start-up survival rates. Chicago Booth Review, https://review.chicagobooth.edu/entrepreneurship/2017/article/surprising-numbers-behind-start-survival-rates.

[15] Earnhart, Dietrich. (2004a). "Panel Data Analysis of Regulatory Factors Shaping Environmental Performance." *Review of Economics and Statistics* 86(1):391–401.

[16] ———. (2004b). "Regulatory Factors Shaping Environmental Performance at Publicly-Owned Treatment Plants." *Journal of Environmental Economics and Management* 48 (1): 655–81. https://doi.org/10.1016/j.jeem.2003.10.004.

[17] Earnhart, Dietrich, and Lana Friesen. (2017). "The Effects of Regulated Facilities' Perceptions About the Effectiveness of Government Interventions on Environmental Compliance." *Ecological Economics* 142 (December): 282–94. https://doi.org/10.1016/j.ecolecon.2017.06.014.

[18] Earnhart, Dietrich, and Kathleen Segerson. (2012). "The Influence of Financial Status on the Effectiveness of Environmental Enforcement." *Journal of Public Economics* 96(9–10):670–84.

[19] Eckert, Heather. (2004). "Inspections, Warnings, and Compliance: The Case of Petroleum Storage Regulation." *Journal of Environmental Economics and Management* 47(2):232–59.

[20] Esworthy, Robert. (2014). Federal Pollution Control Laws: How Are They Enforced? Congressional Research Service.

[21] Farenthold, D. A. (2010). Perdue, poultry farms sued for polluting Chesapeake Bay. Washington Post, March 2.

[22] Foulon, Jérôme, Paul Lanoie, and Benoît Laplante. (2002). "Incentives for Pollution Control: Regulation or Information?" *Journal of Environmental Economics and Management* 44(1):169–87.

[23] Friesen, Lana. 2003. "Targeting Enforcement to Improve Compliance with Environmental Regulations." *Journal of Environmental Economics and Management* 46(1):72–85.

[24] Giles, Cynthia. 2020. "Next Generation Compliance: Environmental Regulation for the Modern Era." *Harvard Environmental & Energy Law Program*

[25] Glicksman, R. L., & Earnhart, D. H. (2007). The comparative effectiveness of government interventions on environmental performance in the chemical industry. *Stanford Environmental Law Journal*, 26, 317.

[26] Gray, Wayne B., and Mary E. Deily. (1996). "Compliance and Enforcement: Air Pollution Regulation in the U.S. Steel Industry." *Journal of Environmental Economics and Management* 31 (1): 96–111. https://doi.org/10.1006/jeem.1996.0034.

[27] Gray, Wayne B., and Carol Adaire Jones. (1991). "Are Osha Health Inspections Effective? A Longitudinal Study in the Manufacturing Sector." *The Review of Economics and Statistics* 73 (3): 504–8. https://doi.org/10.2307/2109575.

[28] Gray, W. B., & Shimshack, J. P. (2011). The effectiveness of environmental monitoring and enforcement: A review of the empirical evidence. *Review of Environmental Economics and Policy*, 5(1), 3-24.

[29] Goeringer, P. (2013). Understanding agricultural liability: Maryland's right to farm law. Center for Agricultural and Natural Resource Policy Fact Sheet, University of Maryland, College Park.

[30] Harford, Jon D. (1987). "Self-Reporting of Pollution and the Firm's Behavior under Imperfectly Enforceable Regulations." *Journal of Environmental Economics and Management* 14(3):293–303.

[31] ———. (1991). "Measurement Error and State-Dependent Pollution Control Enforcement." *Journal of Environmental Economics and Management* 21(1):67–81.

[32] Harford, Jon D., and Winston Harrington. (1991). "A Reconsideration of Enforcement Leverage When Penalties Are Restricted." *Journal of Public Economics* 45(3):391–95.

[33] Harrington, W. (1988). Enforcement leverage when penalties are restricted. *Journal of Public Economics*, 37(1), 29-53.

[34] Hayes, Dermot, Cathy Kling, and John Lawrence. (2016). "Economic Evaluation of Governor Branstad's Water Quality Initiative." *CARD Policy Briefs*, 10.

[35] Helland, E. (1998). The enforcement of pollution control laws: Inspections, violations, and self-reporting. *Review of Economics and Statistics*, 80(1), 141-153.

[36] Heyes, A. G. (1994). Environmental enforcement when 'inspectability' is endogenous: A model with overshooting properties. *Environmental and Resource Economics*, 4(5), 479-494.

[37] ———. (2000). Implementing environmental regulation: enforcement and compliance. *Journal of Regulatory Economics*, 17(2), 107-129.

[38] ———. (2002). A theory of filtered enforcement. *Journal of Environmental Economics and Management* 43(1), 34-46.

[39] Heyes, A. G. and N. Rickman. (1999). Regulatory dealing—revisiting the Harrington paradox. *Journal of Public Economics* 72(3), 361–378.

[40] Innes, Robert. 1999a. "Remediation and Self-Reporting in Optimal Law Enforcement." *Journal of Public Economics* 72(3):379–93.

[41] ———. 1999b. "Self-Policing and Optimal Law Enforcement When Violator Remediation Is Valuable." *Journal of Political Economy* 107(6):1305–25.

[42] ———. (2001). "Violator Avoidance Activities and Self-Reporting in Optimal Law Enforcement." *Journal of Law, Economics, and Organization* 17(1):239–56.

[43] Kaplow, L., & Shavell, S. (1994). Optimal law enforcement with self-reporting of behavior. *Journal of Political Economy*, 102(3), 583-606.

[44] Kambhu, J. (1989). Regulatory standards, compliance and enforcement. *Journal of Regulatory Economics* 1(2), 103–114.

[45] Keiser, David A, and Joseph S Shapiro. (2019). "Consequences of the Clean Water Act and the Demand for Water Quality." *The Quarterly Journal of Economics* 134 (1): 349–96. https://doi.org/10.1093/qje/qjy019.

[46] Khanna, Madhu, Wilma Rose H. Quimio, and Dora Bojilova. (1998). "Toxics Release Information: A Policy Tool for Environmental Protection." *Journal of Environmental Economics and Management* 36 (3): 243–66. https://doi.org/10.1006/jeem.1998.1048.

[47] Langpap, Christian, and Jay P. Shimshack. (2010). "Private Citizen Suits and Public Enforcement: Substitutes or Complements?" *Journal of Environmental Economics and Management* 59(3):235–49.

[48] Laplante, Benoıt, and Paul Rilstone. (1996). "Environmental Inspections and Emissions of the Pulp and Paper Industry in Quebec." *Journal of Environmental Economics and Management* 31 (1): 19–36. https://doi.org/10.1006/jeem.1996.0029.

[49] Lawley, C., Lichtenberg, E., & Parker, D. (2009). Biases in nutrient management planning. *Land Economics*, 85(1), 186-200.

[50] Lichtenberg, E., Parker, D., Lane, S. (2010). Best Management Practice Use and Nutrient Management in Maryland: A 2010 Snapshot. Center for Agricultural and Natural Resource Policy, University of Maryland, College Park.

[51] Lim, J. (2016). The impact of monitoring and enforcement on air pollutant emissions. *Journal of Regulatory Economics*, 49(2), 203-222.

[52] Livernois, John, and C. J. McKenna. (1999). "Truth or Consequences Enforcing Pollution Standards with Self-Reporting." *Journal of Public Economics*, 26.

[53] Magat, Wesley A., and W. Kip Viscusi. (1990). "Effectiveness of the EPA's Regulatory Enforcement: The Case of Industrial Effluent Standards." *The Journal of Law and Economics* 33 (2): 331–60. https://doi.org/10.1086/467208.

[54] Malik, A. S. (1990). Avoidance, screening and optimum enforcement. *The RAND Journal of Economics*, 341-353.

[55] Malik, A. S. (1993). Self-reporting and the design of policies for regulating stochastic pollution. *Journal of Environmental Economics and Management*, 24(3), 241-257.

[56] Malik, A. S. (2014). The desirability of forgiveness in regulatory enforcement. *Journal of Regulatory Economics* 46(1), 1-22.

[57] Muehlenbachs, Lucija, Stefan Staubli, and Mark A. Cohen. (2016). "The Impact of Team Inspections on Enforcement and Deterrence." *Journal of the Association of Environmental and Resource Economists* 3(1):159–204.

[58] Muoghalu, Michael I., H. David Robison, and John L. Glascock. 1990. "Hazardous Waste Lawsuits, Stockholder Returns, and Deterrence." *Southern Economic Journal* 57 (2): 357. https://doi.org/10.2307/1060617.

[59] Maryland Water Quality Improvement Act of 1998, 15 MD §8-801–8-806 (1998).

[60] Maryland Department of Agriculture (MDA). (2014). Ag-Brief nutrient management programs. Retrieved from http://mda.maryland.gov/Documents/ag_brief/AgBrief_NM.pdf

[61] McCann, L. M. (2009). Transaction costs of environmental policies and returns to scale: the case of comprehensive nutrient management plans. *Review of Agricultural Economics*, 31(3), 561-573.

[62] McClelland, J.D. and J.K. Horowitz, J.K. (1999). The costs of water pollution regulation in the pulp and paper industry. *Land Economics* 75, 220-232.

[63] Nadeau, Louis W. (1997). "EPA Effectiveness at Reducing the Duration of Plant-Level Noncompliance." *Journal of Environmental Economics and Management* 34(1):54–78.

[64] Nickell, Stephen. 1981. "Biases in Dynamic Models with Fixed Effects." *Econometrica* 49(6):1417–26.

[65] NOAA. (2019). "NOAA Forecasts Very Large 'Dead Zone' for Gulf of Mexico." National Oceanic and Atmospheric Administration, Silver Spring, MD.

[66] Nowell, Clifford, and Jason Shogren. (1994). "Challenging the Enforcement of Environmental Regulation." *Journal of Regulatory Economics* 6(3):265–82.

[67] Nyborg, Karine, and Kjetil Telle. (2004). "The Role of Warnings in Regulation: Keeping Control with Less Punishment." *Journal of Public Economics* 88 (12): 2801–16. https://doi.org/10.1016/j.jpubeco.2004.02.004.

[68] Nyborg, Karine, and Kjetil Telle. (2006). "Firms' Compliance to Environmental Regulation: Is There Really a Paradox?" *Environmental and Resource Economics* 35(1):1–18.

[69] Olmstead, S. M. (2010). "The Economics of Water Quality." *Review of Environmental Economics and Policy* 4 (1): 44–62. https://doi.org/10.1093/reep/rep016.

[70] Phillips, S., & McGee, B. (2016). Ecosystem Service Benefits of a Cleaner Chesapeake Bay. *Coastal Management*, 44(3), 241-258.

[71] Polinsky, A. M., & Shavell, S. (2000). The economic theory of public enforcement of law. *Journal of Economic Literature*, 38(1), 45-76.

[72] Polinsky, A. Mitchell, and Steven Shavell. (2007). The Theory of Public Enforcement of Law." *Handbook of Law and Economics* 1. https://doi.org/10.1016/S1574-0730(07)01006-7.

[73] Raymond, Mark. 1999. "Enforcement Leverage When Penalties Are Restricted: A Reconsideration under Asymmetric Information." *Journal of Public Economics* 73(2):289–95.

[74] Ringleb, Al H., and Steven N. Wiggins. 1990. "Liability and Large-Scale, Long-Term Hazards." *Journal of Political Economy* 98(3):574–95.

[75] Rousseau, Sandra. (2009). "The Use of Warnings in the Presence of Errors." *International Review of Law and Economics* 29 (3): 191–201. https://doi.org/10.1016/j.irle.2009.01.001.

[76] Shimshack, Jay P. (2014). "The Economics of Environmental Monitoring and Enforcement." *Annual Review of Resource Economics* 6 (1): 339–60. https://doi.org/10.1146/annurev-resource-091912-151821.

[77] Shimshack, Jay P., and Michael B. Ward. (2005). "Regulator Reputation, Enforcement, and Environmental Compliance." *Journal of Environmental Economics and Management* 50 (3): 519–40. https://doi.org/10.1016/j.jeem.2005.02.002.

[78] ———. (2008). “Enforcement and Over-Compliance.” *Journal of Environmental Economics and Management* 55 (1): 90–105. https://doi.org/10.1016/j.jeem.2007.05.003.

[79] Stafford, Sarah L. (2002). “The Effect of Punishment on Firm Compliance with Hazardous Waste Regulations.” *Journal of Environmental Economics and Management* 44 (2): 290–308. https://doi.org/10.1006/jeem.2001.1204.

[80] Stefanski, Stephanie F., and Jay P. Shimshack. (2016). “Valuing Marine Biodiversity in the Gulf of Mexico: Evidence from the Proposed Boundary Expansion of the Flower Garden Banks National Marine Sanctuary.” *Marine Resource Economics* 31 (2): 211–32. https://doi.org/10.1086/685109.

[81] Stranlund, John K., and Carlos A. Chavez. (2002). “Effective Enforcement of a Transferable Emissions Permit System with a Self-Reporting Requirement.” *Journal of Regulatory Economics* 19.

[82] Telle, Kjetil. 2009. “The Threat of Regulatory Environmental Inspection: Impact on Plant Performance.” *Journal of Regulatory Economics* 35 (2): 154–78. https://doi.org/10.1007/s11149-008-9074-z.

[83] ———. 2013. “Monitoring and Enforcement of Environmental Regulations.” *Journal of Public Economics* 99 (March): 24–34. https://doi.org/10.1016/j.jpubeco.2013.01.001.

[84] USEPA. 2005. “Limited Knowledge of the Universe of Regulated Entities Impedes EPA’s Ability to Demonstrate Changes in Regulatory Compliance,” United States Environmental Protection Agency. 2005-P-00024, September 19, 2005.

[85] ———. 2013. “Criminal Provisions of the Clean Water Act.” Data and Tools. US EPA. May 3, 2013. https://www.epa.gov/enforcement/criminal-provisions-clean-water-act.

[86] ———. 2017. “History of the Clean Water Act.” Overviews and Factsheets. United States Environmental Protection Agency. 2017. https://www.epa.gov/laws-regulations/history-clean-water-act.

[87] ———. 2019a. “Clean Water Act (CWA) Compliance Monitoring | Compliance | US EPA.” United States Environmental Protection Agency. 2019.

[88] ———. 2019b. “EPA Not Effectively Implementing the Lead-Based Paint Renovation, Repair and Painting Rule,” United States Environmental Protection Agency.

[89] WHO. 2004. “Sulfate in Drinking-Water.”

[90] Yoon, Taeyeon, Charles Rhodes, and Farhed A. Shah. 2015. “Upstream Water Resource Management to Address Downstream Pollution Concerns: A Policy Framework with Application to the Nakdong River Basin in South Korea.” *Water Resources Research* 51 (2): 787–805. https://doi.org/10.1002/2013WR014201.