The Economics of Enforcing Emissions Markets: A Review of the Literature

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February 10, 2017

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Abstract: This article reviews the economic literature on enforcing emissions permit markets. This literature has produced hypotheses about firms' compliance choices and permit market outcomes, tests of these hypotheses with economic experiments, and insights about the efficient design of enforcement strategies for emissions markets. The findings of the literature are used to identify lessons concerning enforcement and compliance in international markets that are aimed at controlling greenhouse gases.

JEL Codes: K42, L51, Q58

Introduction

Despite the advantages of market-based environmental policies over traditional command-and control approaches, these programs will not perform as expected if they are not enforced well. Although there are several reviews of the economic literature on enforcing environmental policies, including Cohen (1999), Heyes (2000), Gray and Shimshack (2011), and Shimshack (2014), to date, there has not been a thorough review of the literature that focuses specifically on enforcing emissions markets. The purpose of this article is to review the body of literature that has emerged on the economics of compliance and enforcement in emissions trading programs.

The basic structure of an emissions market involves a cap on the aggregate emissions of a pollutant from a set of polluting firms. This cap is often reduced over time. Emissions permits consistent with the cap are allocated to the firms, and they may use these permits to justify their emissions in the current compliance period, sell excess permits to other firms, or purchase additional permits from other firms. Most programs also allow firms to save permits for use or sale in the future, and some programs allow firms to borrow permits from future permit allocations. The basic enforcement problem in emissions markets is to make sure that firms hold enough permits to cover their emissions in a compliance period.

The literature on enforcing emissions markets follows the standard economic model for analyzing the monitoring and enforcement of regulations. In this model, profit-maximizing, (typically) risk-neutral firms choose whether to violate their emissions permits by balancing the gain from doing so against the expected sanction. This model is then used to derive hypotheses about firms' compliance behavior and the effects of enforcement on the performance of emissions markets. Unfortunately, empirical tests of these results have been limited because of the lack of useful data on compliance choices in existing emissions markets. Programs that have achieved very high rates of compliance have too little variation in compliance choices to conduct meaningful statistical tests, and to date, there has been little analysis of compliance behavior in programs that have had significant noncompliance. Consequently, a number of studies have used laboratory experiments to test hypotheses related to compliance in emissions markets. [1]

Results from both theory and experiments have also been used to draw conclusions about how to design efficient enforcement strategies. Although in principle the enforcement component of a trading program should be determined jointly with all of the program's elements to maximize expected social welfare, the literature has often considered other objectives, including minimizing aggregate noncompliance given an exogenous enforcement budget and achieving an exogenous compliance target cost-effectively.[2]

The remainder of this article is organized as follows. First, to provide some institutional context, the next section presents a brief overview of some of the enforcement strategies used in existing and proposed emissions trading programs.[3] This is followed by a review of the fundamental theory of compliance and enforcement in emissions markets, and experimental tests of key hypotheses from this theory. Then I review the literature on the design of enforcement strategies for emissions markets, In the penultimate section, I use results from the literature to identify lessons about enforcing greenhouse gas trading markets. I present conclusions in the final section.

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[1]See Friesen and Gangadharan (2013) for a review of the extensive literature that uses laboratory experiments to evaluate various aspects of emissions markets.

[2] Shimshack (2014) discusses the limitations of the economic approach to analyzing regulatory enforcement. For example, this approach tends to ignore the possibility that compliance is motivated by ethical considerations or by social norms, or that firms may fail to optimize as perfectly as economists assume.

[3] I consider only the enforcement provisions of air emissions markets. I do not consider water quality trading programs, which have unique monitoring and enforcement challenges that are not addressed well in the existing literature on enforcing emissions markets. See Fisher-Vanden and Olmstead (2013) for a recent review of the difficulties of designing and managing water quality trading programs.

Enforcement Strategies: Institutional Context

The fundamental challenge for enforcing emissions markets is ensuring that polluting firms hold enough permits to cover their current emissions. This requires careful monitoring with the goal of comparing firms' permit holdings with their emissions, as well as sanctions for firms that fail to hold sufficient permits or mislead regulators about their actual compliance status.

In this section, I briefly review methods for monitoring and penalizing noncompliance that are employed in actual and proposed emissions markets, as well as accounts of the compliance performance of some existing programs.

Monitoring

Enforcement in emissions markets requires that regulators have systems in place to track emissions permits so that they know the number of permits a source holds at any point in time. However, it is much more challenging to monitor firms' emissions. Monitoring emissions can be done directly with continuous emissions monitoring systems, which measure the continuous flow of pollution leaving a facility. For example, the largest pollution sources in the U.S. Environmental Protection Agency (EPA) SO_2 Allowance Trading Program and NO_X Budget Trading Program were required to install these systems.[4] The other option is to allow firms to estimate their emissions. Smaller firms in the EPA's SO_2 and NO_X emissions markets as well as

[4] It appears that environmental advocacy groups insisted on the use of continuous emissions monitoring systems in the SO2 Allowance Trading Program (Stavins 1998), which suggests that it might be useful to explore the political economy of enforcement choices in the development of emissions markets. I thank a referee for this suggestion.

nearly all firms in the European Union Emissions Trading Scheme (EU ETS) estimate their emissions rather than monitoring them directly.[5]

As with most environmental law, emissions markets rely heavily on self-monitoring and self-reporting of data used to determine compliance. This data includes emissions or estimated emissions, the data used to produce these estimates, and quality assurance and quality control information related to the operation of monitoring technologies. Some programs, like the EU ETS and California's greenhouse gas market, require that firms' emissions reports be verified by a certified, independent auditor (McAllister 2010, California Air Resources Board 2011).

Sanctions

The comparison of a regulated firm's permit holdings with its actual (or estimated) emissions for a compliance period determines whether the firm is violating its permits. The sanctions imposed on firms that have excess emissions vary greatly across emissions markets.

Automatic financial penalties and offsets

Some programs sanction permit violations with an automatic financial penalty and require a surrender of permits in the next compliance period to offset the shortfall. For example, in 1990, the permit violation penalty in the U.S. SO_2 Allowance Trading Program was set at $2,000 per ton of excess emissions, and it was adjusted annually for inflation over time. In addition, the excess emissions had to be offset using permit allocations in the following year (US EPA 2010). Similarly, the EU ETS includes a permit violation penalty of €100 per ton and excess emissions

[5] These estimates tend to be based on formulas that combine activity data like fuel and raw material use with emissions factors that specify emissions per unit of the activity (Kruger, Oates and Pizer 2007, McAllister 2010).

must be offset in the following year (Chevallier 2012). Other programs use permit offsets as the main penalty. For example, a firm's permit violation in the U.S. NO_X Budget Trading Program was penalized with a three-to-one reduction in its permit allocation in the next compliance period (US EPA 2009). Similarly, permit violations under California's greenhouse gas trading program are punished with a four-to-one offset (California Air Resources Board 2011). In nearly all trading programs, the marginal sanctions for permit violations are substantially higher than the prevailing permit prices.

Tying penalties to permit prices

A little-used but potentially important form of sanction ties a financial penalty directly to prevailing permit prices. The proposed (but not enacted) U.S. Clear Skies Initiative, which sought to reduce emissions of SO_2, NO_X, and mercury from electric power generators, included a permit violation penalty that was to be one to three times the clearing price in a recent permit auction (US EPA 2003). Similarly, the American Clean Energy and Security Act of 2009 (US Congress 2009), which sought to control greenhouse gas emissions in the U.S., included a permit violation penalty that was set at twice the market value of CO_2 permits during a compliance year. Perhaps the only example of this form of sanction that is actually in use is in some of the pilot programs for China's CO_2 emissions trading system. The Beijing and Shenzhen pilot programs set penalties for excess emissions at three to five times the market price of CO_2 allowances (Zhang 2015).

Penalties for false reporting

The penalties for false reporting of emissions and other compliance data can also be significant. For example, the U.S. Clean Air Act authorizes civil and criminal sanctions for false reporting under the EPA's emissions markets (Tietenberg 2006, McAllister 2010). There is a lot of variation among member states of the EU ETS in the penalties for reporting violations, but they include both financial sanctions and the threat of prison terms (European Environment Agency 2008). As I will discuss later, the main challenge for maintaining compliance in emissions markets may actually be how to motivate accurate reporting.

Performance

The performance of enforcement strategies for emissions markets has ranged from significant noncompliance to near-perfect compliance.[6] For example, Montero, Sanchez and Katz (2002) and Palacios and Chavez (2005) argue that development of an emissions trading program for suspended particulates in Santiago, Chile was hampered by weak enforcement and significant noncompliance. McAllister (2010) reports significant compliance problems in the Regional Clean Air Incentives Market program to control emissions of NO_x and SO_X in southern California. In contrast, the EPA's emissions trading programs have achieved very high rates of compliance (US EPA 2009, 2010). Finally, it has been reported that China's pilot trading programs for CO_2 have achieved very high rates of compliance in the first compliance period (Zhang 2015).

[6] Although cases of fraud in the EU ETS have received much attention (Interpol 2013), these cases involved evasion of the EU value added tax, as well as phishing and hacking schemes to steal permits from company registries. This sort of financial fraud is very different from the problem of firms failing to hold sufficient permits to cover their emissions, which is the focus of the economic literature on enforcing emissions markets.

Fundamentals of Compliance and Enforcement in Emissions Markets

This section reviews the literature on the fundamental economics of compliance and enforcement in emissions markets. I start by describing a static model of compliance in competitive emissions markets. This model produces hypotheses about compliance behavior in emissions markets, many of which have been tested with economic experiments. I then consider how enforcement affects the standard conclusion about the cost-effectiveness of competitive emissions markets. Finally, I review how compliance behavior in emissions markets is affected by market power and transaction costs. While most of this section focuses on results about how enforcement of emissions markets affects firms' compliance choices and market performance, these results often lead directly to lessons about how best to design enforcement strategies.

Compliance Behavior and Market Effects of Enforcement

In a simple static model of compliance in a competitive emissions market, a risk-neutral firm's choice of emissions and the number of permits to hold are based on minimizing its costs of abatement, plus its expenditures or receipts from permit transactions, plus the expected penalty should it decide *not* to hold enough permits to cover its emissions. The expected penalty consists of the probability that the firm is inspected and a violation is discovered and a financial sanction that is increasing and convex in the size of the firm's violation. All of the theoretical results I review here assume that firms choose a positive amount of emissions and hold a positive number of permits.

Under these conditions, a firm will hold enough permits to cover its emissions if and only if the prevailing permit price is not less than the expected marginal penalty. Moreover, if the firm decides to violate its permits, it will choose a violation level at which the permit price is equal to the expected marginal penalty (Malik 1990, Keeler 1991). Thus, the permit price plays a key role in compliance decisions and enforcement. This is because it is a firm's observable marginal benefit of noncompliance. In addition, given reasonable assumptions about the probability of inspection and discovery of a violation, a firm's choice of emissions follows the familiar rule of equating the permit price to its marginal abatement costs. These simple choice rules, combined with the equilibrium in emissions permit markets, yield fundamental results about firms' compliance, emissions, and technology choices in these markets.

Independence of compliance choices from firm characteristics

Stranlund and Dhanda (1999) point out that since firms' compliance decisions depend only on the permit price and the enforcement strategy they face, differences in their compliance choices will not depend on differences in their abatement costs and initial permit allocations. In theory, then, there is no reason for regulators to believe that certain firms will be more likely to be noncompliant or tend toward higher violations even though they may have different abatement or production technologies, or different initial permit allocations. This suggests that enforcement officials cannot increase the productivity of their efforts by targeting firms (perhaps with differential monitoring) based on differences in their observable characteristics. This simplifies enforcement because it means that regulators do not need information about firms' characteristics, which may be difficult to obtain, to devise an effective enforcement strategy; all they need is to observe the permit price.

The situation is very different for firms that face command-and-control standards. In particular, a firm's decision about whether to comply with an emissions standard is determined by the relationship between its marginal abatement cost and the marginal expected penalty for failing to comply. Thus, in the case of fixed standards, firm-level characteristics are important determinants of compliance (Garvie and Keeler 1994). Gray and Shadbegian (2005 and 2007) and Earnhart (2009) provide empirical support for this conclusion. Because firms' abatement costs are an important determinant of their compliance choices when they face emissions standards, regulators can improve the productivity of their enforcement efforts by targeting firms based on characteristics that are correlated with their abatement costs. However, this would not be a productive strategy in a competitive emissions market.

Murphy and Stranlund (2007) provide experimental support for the conclusion that regulators of emissions markets cannot increase the productivity of their enforcement efforts by targeting firms based on their individual characteristics. They found that laboratory subjects' violations were independent of differences in their abatement costs, as predicted. However, they also found that subjects who were predicted to buy permits tended to have higher violations than those who were predicted to sell permits. While this result may suggest that regulators monitor permit buyers more closely than sellers, Murphy and Stranlund (2007) also found that the marginal productivity of increased enforcement in reducing violations was independent of differences in both abatement costs and initial permit allocations. This suggests that if a regulator's objective is to use scarce enforcement resources to maximize aggregate compliance in an emissions market, then there is no theoretical or empirical justification for targeting firms based on their individual characteristics.

Direct and indirect price effects of enforcement

Changes in the regulatory environment can directly affect compliance choices, as well as having indirect effects on compliance incentives through changes in the permit price. For example, increased monitoring or stricter sanctions will lead noncompliant firms to purchase more permits to reduce their violations. This is the direct effect of enforcement on compliance. However, the increased demand for permits may also increase the permit price, which motivates firms to increase their violations. This indirect effect of increased enforcement on compliance works in the opposite direction from the direct effect. In theory, the direct effect will outweigh the indirect effect and greater enforcement will thus result in greater compliance. However, it is important for regulators to recognize that the effectiveness of stricter enforcement in reducing noncompliance is partially offset by a countervailing price effect. Moreover, the fact that a firm – whether it is compliant or not – chooses its emissions to equate its marginal abatement costs with the permit price implies that its choice of emissions does not depend directly on the enforcement strategy it faces; rather, emissions will fall only if increased enforcement leads to a higher permit price. In a laboratory setting, Murphy and Stranlund (2006) confirmed these hypotheses about the direct and indirect price effects of enforcement.

Technology adoption

The special nature of compliance decisions in emissions markets has important implications for the adoption and diffusion of new cost-saving abatement technologies. Consider a firm that violates a fixed emissions standard. If the firm adopts a new abatement technology, it will reduce its violation because its marginal abatement costs fall. This is not the case for a firm in an emissions market. Arguedas, Camacho and Zofio (2010) and Villegas-Palacios and Coria (2010) show that because firms' violation choices do not depend on their abatement costs, a firm that adopts a new abatement technology will not change its violation level if the permit price does not change. However, if the technology is diffused enough to lower the permit price, then all firms – not only those that adopt the new technology – will reduce their violations. This suggests that policies to promote cost-saving abatement technologies can also reduce firms' incentives to violate their permits, but only if the policies lead to lower permit prices.

Enforcement and the Cost-Effectiveness of Emissions Markets

Malik (1990) appears to have been the first to show that under reasonable assumptions about the structure of a fixed enforcement strategy, each firm in a competitive emissions market, whether it is compliant or not, will choose a level of emissions that equates its marginal abatement costs with the permit price. This implies that aggregate abatement costs are minimized even though aggregate emissions may exceed the permit cap because of weak enforcement. Stranlund, Murphy and Spraggon (2013) tested this hypothesis with laboratory experiments and found that their laboratory markets came very close to minimizing aggregate abatement costs, despite imperfect enforcement and significant violations.

Although we might expect a competitive permit market to minimize aggregate abatement costs, even with weak enforcement, Malik (1992) has shown that an emissions market will not, in general, minimize the *sum* of abatement costs and enforcement costs. Competitive permit trading minimizes the aggregate abatement costs of reaching an aggregate emissions standard because trading produces a uniform price that results in firms choosing levels of emissions that equalize their marginal abatement costs. In contrast, Stranlund, Chavez and Villena (2009) show that minimizing the sum of aggregate abatement and enforcement costs might require differential permit prices to account for differences in marginal enforcement costs across firms. Differences in marginal enforcement costs may be due to differences in a regulator's ability to monitor the emissions of different firms, as well as the firms' responsiveness to changes in enforcement. Differential prices can be implemented in emissions markets by ensuring that the rates at which permits trade among firms differ from one-to-one.

Whether it is worthwhile to implement differential permit prices to account for differences in marginal enforcement costs depends on whether regulators have enough information to detect these differences and whether the differences are significant enough to justify the added complexity of implementing differential pricing. Policies that produce differential prices through the use of trading ratios have been proposed to account for non-uniformly mixed pollutants (e.g., Muller and Mendelsohn 2009), non-point source pollution (e.g., Hung and Shaw 2005), and carbon offset credits (Bento, Ho and Ramirez-Basora 2015). However, I know of no proposals to account for differences in enforcement costs in this way. Consequently, in the remainder of the article I focus on enforcing markets in which permit prices are uniform across firms.

Impacts of Market Imperfections

The theory and experiments discussed thus far have assumed perfect competition. However, there are several market imperfections that can result in inefficient outcomes in permit markets. These market imperfections include the presence of market power and transaction costs, which can have important implications for both compliance behavior and enforcement.

Market power

In extending Hahn's (1984) seminal paper on market power in emissions markets to account for compliance and enforcement, van Egteren and Weber (1996), Malik (2002) and Chavez and Stranlund (2003) found that the presence of market power can affect the compliance incentives for all firms. More specifically, if a powerful permit buyer limits the number of permits it buys to hold down the permit price, this reduces the incentive for other firms in the market to violate their permits. At the same time, the marginal benefit of noncompliance is higher for the powerful firm than for competitive firms because the marginal benefit of noncompliance for a powerful permit buyer is the sum of the permit price and the marginal increase in this price as the firm buys additional permits. These effects are reversed if the dominant firm sells permits. Recall that enforcement is simpler in a perfectly competitive market because regulators have no reason to target enforcement at specific firms and they do not need information about firms' abatement costs to design an effective enforcement strategy. These features disappear in the presence of powerful firms. Because the compliance incentives for powerful firms are different from those for competitive firms, there is a rationale for regulators to target powerful firms with more or less enforcement pressure, depending on whether they are permit buyers or sellers.

Transaction costs

Transactions costs can also have a significant impact on compliance behavior and enforcement of emissions trading programs. Stavins (1995) showed that variable transaction costs drive a wedge between the price that buyers pay for permits and the price that sellers receive. This means that transaction costs can also drive a wedge between the compliance incentives of buyers and sellers, with permit buyers being more likely than sellers to violate their permits. As with market power, transaction costs associated with permit trading can increase the complexity of enforcing emissions markets.

The Design of Enforcement Strategies

Thus far, I have focused primarily on compliance and market results under the assumption that the parameters of an emissions trading program (monitoring, penalties, and permit supply) are exogenous. I now turn specifically to the design of enforcement strategies. I begin by examining the challenge of enforcing emissions markets that allow for intertemporal trading of emissions permits, which highlights the critical role played by self-reporting of compliance data. I then turn to the efficient design of emissions markets, focusing specifically on the optimal level of noncompliance in these programs. Next, I examine the interaction between enforcement and uncertainty about firms' abatement costs in the efficient design of emissions markets. It is important to note that all of the literature I review here assumes that permit markets are perfectly competitive.

Enforcement of Intertemporal Permit Trading and the Role of Self-Reporting

The banking of emissions permits allows firms to cost-effectively shift their abatement across time and to hedge against the risk associated with uncertain abatement costs, emissions, and permit prices.[7] Most emissions markets allow limited banking of emissions permits. For example, the U.S. SO_2 Allowance Trading Program allowed firms to save permits for future use or sale, but did not allow them to borrow against future permit allocations. The U.S. NO_X Budget

[7] Ellerman and Montero (2007) empirically analyze permit banking under the SO_2 Allowance Trading Program, and Chevallier (2012) describes banking and borrowing opportunities under the EU ETS.

Trading Program had similar banking provisions, except it imposed a heavy discount on saved permits if the total amount banked by all firms reached a particular limit (US EPA 2009). Some programs for greenhouse gas emissions also allow restricted permit borrowing. These programs include the EU ETS and the proposed American Clean Energy and Security Act of 2009 (US Congress 2009).

Innes (2003) was the first to use a model of intertemporal permit trading to examine the problem of compliance in intertemporal emissions markets. In his model, permit banking is motivated by stochastic emissions. Firms that have imperfect control of their emissions can find themselves short of permits at the end of a compliance period. However, Innes (2003) demonstrated that allowing intertemporal permit trading can eliminate costly sanctions for firms' violations because it allows firms to borrow against their future permit allocations to offset any current permit shortfall. Moreover, firms may save permits as a hedge against permit shortfalls in the future. Clearly, firms that hold excess permits for this purpose are compliant in the current period.

The importance of providing incentives for accurate self-reporting

In contrast to Innes (2003), who assumed a very simple enforcement strategy, Stranlund, Costello, and Chavez (2005) investigated the optimal design of monitoring and sanctioning strategies in intertemporal trading environments. Their most important contribution is to highlight the importance of self-reported compliance data. First, they note that the combination of imperfect emissions monitoring and bankable permits means that firms must self-report their emissions. This is because if a firm is not monitored in a period, then its emissions report is the only information available to determine how many permits it is using for current compliance purposes and how many it is banking for the future. They also emphasize that misreporting compliance and the failure to hold sufficient permits must be separate violations, because a firm that holds enough permits to cover its emissions in a particular period may still be motivated to underreport its emissions to increase the size of its permit bank.[8]

Stranlund, Costello, and Chavez (2005) also show that the high permit violation penalties (relative to permit prices) that characterize many emissions trading programs may have little impact on maintaining compliance. This is because the strong incentive to bank permits and the typical requirement that any permit violation be offset by a reduction in a future permit allocation effectively eliminates the incentive for firms to violate their permits. In principle, permit violation penalties need to cover only the difference between this period's permit price and the present value of next period's price, and thus can normally be very low. In addition, setting a high permit violation penalty cannot be used to reduce monitoring effort. On the contrary, a separate penalty for false reporting to motivate truthful emissions reporting has a significant impact on maintaining permit compliance, and setting this penalty as high as is practicable reduces monitoring costs.[9]

To test the hypothesis that strict sanctions for reporting violations play a more important role in motivating compliance in intertemporal emissions markets than strict sanctions for permit violations, Stranlund, Murphy and Spraggon (2011) examined compliance and banking in a laboratory setting. One of their treatments was parameterized to induce full compliance, but

[8] It is common for environmental regulations to require self-reported compliance data and to make misreporting a separate punishable offense. However, much of the economic literature on self-reported behavior in law enforcement assumes that self-reporting is a *voluntary* activity that can be encouraged by offering lower penalties for voluntarily revealed violations. See Innes (2001) for a review of this literature.

[9] Much of the credit for high compliance rates in the U.S. SO_2 Allowance Trading program, the U.S. NO_X Budget Trading Program, the EU ETS, and other emissions trading programs has been given to the high penalties for permit violations. However, it is important to note that these programs also have very strict penalties for reporting violations.

with reporting and permit violation penalties set below the expected permit price. In fact, the permit violation penalty was set at about one-quarter of the predicted permit price. Reporting and permit compliance rates in this treatment were quite high, about 96 percent and 92 percent compliance, respectively. In another treatment, the authors reduced the monitoring probability by half to investigate the consequences of weak enforcement on intertemporal emissions markets. As expected, there was significant noncompliance, but nearly all of it involved reporting violations, with permit compliance remaining high. These results support the theoretical argument that high permit violation penalties are not necessary in markets with bankable permits, and that the main enforcement challenge in these environments is to motivate accurate self-reporting.

Cason and Gangadharan (2006) also studied compliance and banking with laboratory experiments, but they focused on how the ability to bank permits affects compliance, rather than on the design of enforcement strategies given the ability to bank permits. Monitoring was imperfect in their experiments, so they had subjects report their emissions. Surprisingly, they found that banking led to significant noncompliance and higher emissions. Although they did not explicitly distinguish between misreporting and permit violations in their data analysis, they suggest that "subjects more frequently chose to under-report emissions at the end of the period when they could bank permits" (Cason and Gangadharan 2006, p. 215). In practice, because firms have the ability to increase the size of their permit banks by underreporting their current emissions, they may be motivated to submit false emissions reports. However, it is also clear that enforcement strategies can be designed to encourage truthful reporting.

The evolution of compliance incentives

Another feature of intertemporal emissions trading that has enforcement consequences is the fact that firms' compliance incentives evolve over time as permit prices evolve. For example, banking permits under certainty requires that the nominal price of permits rise at the rate of discount (Rubin 1996), but this increases the incentive for firms to underreport their emissions. To counteract this effect, either sanctions or monitoring intensity must increase with the permit price. Because increasing monitoring is costly but increasing penalties typically is not, sanctions, not the level of monitoring, should respond to price increases. A simple way to achieve this is to make sanctions a constant multiple of realized permit prices. This would keep monitoring effort and compliance choices constant as permit prices increase over time.[10]

The Optimal Level of Non-Compliance

A key issue in the design of any environmental policy is whether its enforcement should seek to motivate full compliance, or whether allowing a certain amount of noncompliance can reduce the costs of reaching environmental goals. Much of the literature on designing emissions markets avoids this issue by assuming that regulators cannot apply enough enforcement pressure to induce full compliance. For example, Stranlund and Dhanda (1999) examined the strategy of an enforcer who seeks to minimize noncompliance with a fixed budget that is not large enough to achieve full compliance. While limited resources are often a factor in regulatory enforcement, an enforcer's budget is an endogenous element in the determination of an optimal emissions market.

[10] Recall that tying sanctions to permit prices was proposed in the U.S. EPA's Clear Skies Initiative and the American Clean Energy and Security Act of 2009, and that this form of sanctions has been implemented in CO_2 trading programs in China.

Another common assumption that precludes full compliance is that penalties are restricted. For example, Montero (2002) assumes that permit violation penalties cannot be set above permit prices. However, this assumption is overly restrictive and uncharacteristic of real emissions markets, where penalties are often many times higher than prevailing permits prices. Others assume away the problem of the optimal level of noncompliance by restricting their analyses to full-compliance outcomes without justifying this choice from an efficiency standpoint (e.g., Malik 1992).

Stranlund (2007) used a static model to examine the issue of the optimal level of noncompliance in an emissions market. In his model, a regulator chooses a supply of emissions permits and an enforcement strategy to minimize the expected costs of achieving a fixed aggregate emissions limit.[11] Expected costs include the firms' abatement costs, the government's monitoring costs, and the expected costs of sanctioning noncompliant firms.[12] Stranlund (2007) found that any static emissions trading scheme that achieves an aggregate emissions goal while tolerating permit violations is more expensive than an alternative policy that achieves the same aggregate emissions but motivates firms to be fully compliant. The principles underlying this result are first, that motivating full compliance eliminates variable sanctioning costs, and second, that there are sufficient levers in a trading program (the permit supply, monitoring, and penalty function) to achieve any level of aggregate emissions with full compliance without increasing monitoring effort or setting higher marginal penalties.

[11] Caffera and Chavez (2011) present additional results about the cost-effectiveness of alternative levels of noncompliance for both emissions standards and emissions markets.

[12] Modeling sanctioning costs is not common in the literature on enforcing environmental policies. In reality, penalizing firms may include the administrative costs associated with collecting penalties, the costs of investigative efforts, the costs of firms' efforts to challenge or avoid the imposition of penalties, and the government's costs of confronting such challenges.

To illustrate these principles, suppose that the expected marginal penalty for permit violations is a constant that is applied to all firms and it is not high enough to induce full compliance with a fixed supply of permits. In this case, the equilibrium price for permits equals the expected marginal penalty; aggregate emissions equate this price to aggregate marginal abatement costs; and aggregate violations equal aggregate emissions minus the supply of permits. Now let's increase the supply of permits by exactly the size of the aggregate violation without changing anything else about the policy. This modification does not change the equilibrium permit price because the permit price remains equal to the expected marginal penalty. Since the permit price does not change, aggregate emissions and aggregate abatement costs do not change either. However, permit violations are eliminated because aggregate emissions are equal to the new permit supply. In this way, variable sanctioning costs are eliminated without incurring other costs, which means the costs of meeting the same aggregate emissions target are reduced.

The result that it is cost-effective to design emissions markets that achieve full compliance is consistent with the experience of several emissions markets that have achieved very high rates of compliance, including the U.S. SO_2 Allowance Trading and NO_X Budget Trading programs. If firms' abatement costs are known with certainty, then the goal of full compliance also applies to the design of an efficient emissions market. This is because motivating full compliance is a cost-minimizing strategy for achieving any given level of aggregate emissions, including the one that balances the costs and benefits of emission control efficiently. However, the issue of the optimal level of noncompliance becomes more complicated when firm's abatement costs are uncertain.

Uncertainty about Firms' Abatement Costs

The challenge of designing policy under uncertainty concerning firms' abatement costs has been a focus of environmental economists for many decades. Weitzman's (1974) derivation of rules for choosing between price and quantity policies continues to be relevant in today's debates about the efficient control of carbon emissions. In particular, it is widely believed that a carbon tax is more efficient than a carbon market because the marginal damage of carbon emissions is almost perfectly flat over a compliance period (Pizer 2002). However, the preference for markets over taxes in some policy circles has generated rapid innovation in hybrid schemes, with the most popular involving tradable permits with price controls, as first proposed by Roberts and Spence (1976). Many recent policies to control greenhouse gases include some form of price control (see Hood 2010, and Newell, Pizer and Raimi 2013).

The first proposals for hybrid schemes for carbon markets involved price ceilings, implemented by allowing firms to purchase additional permits from the government at a pre-determined price (Pizer 2002, Jacoby and Ellerman 2004). These policies are also known as safety valves because they allow firms to escape the limit imposed by the permit supply in case their abatement costs turn out to be significantly higher than expected. Adding a price floor can further improve efficiency by motivating firms to abate emissions below the permit supply if their abatement costs turn out to be lower than expected (Burtraw, Palmer and Kahn 2010).

Enforcement to provide a price ceiling

In fact, the high penalties for permit violations in programs such as the SO_2 Allowance Trading program and the EU ETS can be viewed as price ceilings that can limit high-side abatement cost risk (Jacoby and Ellerman 2004, Stavins 2008). In a more rigorous analysis, Montero (2002) reexamined the prices vs. quantities debate to analyze the effects of imperfect and costly enforcement on the choice between an emissions tax and emissions trading. He found that imperfect enforcement tends to favor emissions trading precisely because the expected marginal penalty can provide the price ceiling that improves the efficiency of emissions trading under abatement cost uncertainty. More specifically, if firms' abatement costs turn out to be very high, the permit price will rise to the expected marginal penalty and firms will violate their permits by increasing their emissions beyond the permitted cap. Thus, uncertainty about firms' abatement costs may justify designing emission markets that result in imperfect compliance when firms' abatement costs are higher than expected.

Efficient enforcement and price controls

However, Stranlund and Moffitt (2014) argue that using the expected marginal penalty to establish a price ceiling is inefficient if an emissions market can be designed that has explicit and well-enforced price controls. Relative to a market with imperfect enforcement (i.e., Montero's model), the adoption of a perfectly enforced tax that allows firms to emit beyond their permit holdings can eliminate the expected costs of sanctioning noncompliant firms without changing the expected emissions and price of the policy. Moreover, a perfectly enforced subsidy for unused permits can provide a price floor that motivates additional abatement when abatement costs are lower than expected. Using imperfect enforcement to provide a price ceiling cannot address the possibility of abatement costs being lower than expected. Finally, Stranlund and

Moffitt (2014) show how using the expected marginal penalty as a price ceiling allows abatement cost risk to be transmitted to compliance choices and enforcement costs. Enforcing an emissions trading program with explicit price controls so that firms are always compliant mitigates this transmission of risk.

Lessons for Greenhouse Gas Trading

Although the literature on the economics of enforcing emissions markets has made significant progress, little of this research has focused specifically on the enforcement of markets for controlling greenhouse gas emissions. In this section, I identify lessons from the literature I have just reviewed that can be applied to greenhouse gas markets. I also consider the implications of this literature for two specific features of international greenhouse gas trading: linking emissions markets and emissions offset credits.

Lessons for Designing Enforcement Strategies for Greenhouse Gas Markets

Perhaps the biggest difficulty for designing an effective market for greenhouse gas emissions is obtaining accurate emissions data. Moreover, this task may be more difficult for greenhouse gas control than for other emissions control problems. The first challenge is the sheer number of pollution sources. For example, the EU ETS covers more than 11,000 sources of CO_2 emissions. Moreover, a comprehensive policy would also control emissions of several greenhouse gases. For example, in addition to controlling emissions of CO_2, the American Clean Energy and Security Act of 2009 would have controlled emissions of methane, nitrous oxide, sulfur hexafluoride, perfluorocarbons, nitrogen trifluoride, and hydrofluorocarbons (US Congress

2009). Emissions of these gases can be more difficult to monitor than CO_2 emissions (McAllister 2010).

The approach to emissions monitoring in the EU ETS would appear to provide a reasonable approximation of how monitoring is likely to occur in future trading programs aimed at mitigating climate change. This means that while some firms may be required to (or opt to) employ continuous emissions monitoring systems in future programs, most programs will likely continue to rely on estimates of emissions based on activity data and emissions factors. Thus, self-monitoring and self-reporting of these data will continue to be important elements of enforcement. Moreover, future trading programs will likely allow limited banking and borrowing of permits.

Hence, future greenhouse gas markets – indeed future emissions trading programs generally – are likely to involve imperfect monitoring, heavy reliance on self-reported data, and intertemporal permit trading. The literature I have reviewed here provides six general lessons for enforcing greenhouse gas emissions markets:

1. In reasonably competitive trading programs, there is no need for targeted enforcement based on firm characteristics. That is, characteristics such as whether a firm buys or sells permits, its abatement or production technology, or its choices of inputs or levels of outputs cannot increase the productivity of a regulator's enforcement resources. This lesson does not apply in cases of market power or significant transaction costs.

2. The key to enforcing an intertemporal permit trading program with imperfect monitoring is motivating accurate self-reporting of emissions (or emissions proxies). Once the problem of

getting firms to accurately report emissions has been solved, motivating them to hold sufficient permits to cover their emissions is relatively simple. However, permit compliance is not possible without reporting compliance.

3. High penalties for permit violations, like those found in existing emission markets, have little deterrence value because of permit banking and the standard requirement that permit violations be offset by reductions in future permit allocations. Although stiff sanctions for reporting violations can substitute for monitoring effort, high permit violation penalties cannot.

4. Noncompliance should not be relied on as a safety valve to control the risk of high permit prices. Instead, implementing an explicit price ceiling and floor and enforcing a trading program to achieve full compliance can reduce expected enforcement costs and provide more efficient abatement cost containment.

5. It is important to consider tying sanctions to observed permit prices. This form of sanction can absorb variations in permit prices, thus shielding enforcement effort and compliance outcomes from price changes.

6. Enforcement strategies should be designed to achieve full compliance. This may seem like an obvious lesson, but much of the economic literature on environmental enforcement could leave the impression that it is normally efficient to design policies so that firms are noncompliant. In fact, eliminating the variable costs of sanctioning noncompliant firms is a

powerful motivation for designing trading programs that achieve full compliance. Moreover, there are sufficient levers in emissions markets (e.g., the permit supply, monitoring, and sanctions) to achieve full compliance without incurring additional costs or altering the policy's environmental outcome.

Linking Emissions Markets

International efforts to control greenhouse gas emissions now and in the future will likely consist of many independent national and regional policies, rather than a comprehensive global system. Thus, an important consideration is whether and how to link independent emissions markets. Although there are several ways to link markets, linking usually means that pollution sources in one program can trade permits with pollution sources in other programs. The most important expected benefit of linking emissions markets is the potential to reduce overall abatement costs.[13]

One issue concerning the linking of emissions markets that has not received much attention in the literature is that markets may have different enforcement strategies and compliance performance, and these differences will have consequences across the markets when they are linked. For example, linking markets causes compliance incentives to change as permit prices adjust, and enforcement activities or compliance choices (or both) may also change in response. Thus, linking markets can mitigate or exacerbate existing enforcement and compliance problems.

[13] For discussions of some of the issues associated with linking greenhouse gas markets, see Jaffe, Ranson and Stavins (2009) and Metcalf and Weisbach (2012).

To illustrate, consider a simple model of two countries with domestic emissions markets for CO_2 emissions that are unlinked at first, but the price of CO_2 permits is higher in one of the countries. Now let's assume that total permit supplies do not change after the programs are linked.[14] When the countries link their programs, their prices will equalize as the country that initially had the higher permit price buys permits from firms in the low-price country. The falling price in the country that initially had a higher permit price reduces the incentive for its firms to violate their permits, but the incentive to violate permits increases in the other country as its permit price increases. This means that, depending on the distribution of violations before linking, the lower price in one country may reduce violations in that country while the higher price in the other country may increase violations there. Moreover, enforcement strategies in both countries may adjust to confront the changes in compliance incentives. Ultimately, whether linking leads to higher or lower aggregate emissions will depend on how aggregate violations change.

The connection between enforcement and compliance performance will continue after programs are linked together. In fact, price risk can be transmitted across programs, which has compliance and enforcement consequences. For example, suppose that programs in two countries are linked together, and for some reason marginal abatement costs in one country are higher than expected. The result will be a higher permit price in both countries, thus increasing the noncompliance incentive and placing additional pressure on enforcement resources in both countries. Tying sanctions directly to prevailing permit prices may help mitigate the price effects on compliance and enforcement that are transmitted across linked markets.

[14]Helm (2003) argues that countries may choose their national caps in anticipation of linking with other programs, and shows how this may lead them to choose lower caps.

All of this suggests that it is important to carefully consider the enforcement consequences of linking markets, both in the implementation phase, as prices and compliance incentives adjust to the initial linking, and in administering already-linked markets, as shocks in one market can change prices and compliance incentives across markets.

Offset Credits

Offset credits are emissions reductions that are generated outside of an emissions market that firms can purchase to substitute for their own emissions abatement. Most greenhouse gas trading schemes allow the use of offsets (Hood 2010). In fact, the largest offset market in the world is the Clean Development Mechanism under the Kyoto Protocol, which allows industrialized countries to purchase credits from projects to reduce greenhouse gas emissions in developing countries that are parties to the Protocol. Offset credits can be generated in many ways, including reducing greenhouse gas emissions from industrial facilities, reducing methane emissions from coal mines, wastewater treatment plants, and landfills, and sequestering carbon in forests and soils. The main expected benefit of allowing offset credits is a reduction in the costs of an emissions market. Offset markets may yield additional benefits by producing incentives for technological innovations and promoting the development of institutional capacity to control greenhouse gas emissions in other countries (Sigman and Chang 2011).

However, ensuring that offsets represent real emissions reductions raises serious enforcement concerns. In particular, the number and variety of potential offsets makes monitoring emissions reductions more complex than monitoring large point sources. For example, offset credits may come from a large number of smaller pollution sources and measuring carbon sequestered in forests and soils may be more difficult than measuring greenhouse gas emissions from large industrial sources. In addition, monitoring activities are not simply limited to the performance of an offset project. Typically, offset projects must be additional, meaning that the emissions reduction would not have occurred without the project. Establishing the additionality of an offset project requires gathering information to establish a business-as-usual baseline. Further monitoring and enforcement difficulties arise from differences in the regulatory and legal capacities of regulators in the offset trade (Bushnell 2012). For example, there is a potentially large supply of offset credits from reducing emissions from deforestation and degradation (REDD activities) in developing countries. However, some of these countries lack the institutional capacity for environmental monitoring and enforcement and to control corruption, both of which are necessary for offset credits to be credible (Deveny et al. 2009).

These enforcement challenges are likely to lead to compliance problems in offset markets, as some credits are traded that do not represent actual emissions reductions. However, this does not necessarily imply that offset provisions are counterproductive in terms of controlling aggregate emissions or producing more efficient trading programs. In fact, in a theoretical analysis, Sigman and Chang (2011) show how offset provisions can produce lower aggregate emissions and more efficient markets even if offsets involve higher enforcement costs and significant noncompliance. Of course, enforcement and compliance problems associated with offsets could easily lead to worse environmental and economic outcomes. The point is that these outcomes are not inevitable. Careful estimates of the compliance and cost consequences of including offset provisions in emissions markets are needed to determine whether these provisions are a useful component of emissions markets.

Conclusions

Research and real-world experience have revealed much about the unique compliance and enforcement challenges of emissions markets. This article has sought to highlight important insights from the economic literature concerning the nature of firms' compliance incentives and the effective and efficient design of enforcement strategies. This review has revealed insights about the interdependence of compliance choices and permit prices in emissions markets; the efficiency of implementing enforcement strategies that achieve full compliance in these markets; and the importance of motivating accurate self-reporting to achieve this goal.

However, more research is needed to address the challenges of enforcing markets to control greenhouse gas emissions. In particular, future research should address the efficient enforcement of markets that seek to control multiple pollutants from a wide variety of sources; coordinating the enforcement strategies of greenhouse markets that are linked together; and the effective enforcement of offset credits. More generally, it is important for research into the efficient enforcement of emissions markets to expand as new regulatory innovations in the design of emissions markets emerge.

Acknowledgements: I wish to thank Carlos Chavez, James Murphy, and John Spraggon for many of the ideas in this article, which originated through our collaborations. In addition, Carlo Carraro, Suzanne Leonard, and two anonymous referees provided valuable comments on the article. This research has been supported by a grant from the U.S. Environmental Protection Agency's National Center for Environmental Research (NCER) Science to Achieve Results (STAR) program. Although the research described in this article has been funded wholly or in part by the U.S. EPA through grant number RD-83367201-0, it has not been subjected to the

EPA’s peer and policy review and therefore does not necessarily reflect the views of the Agency, and no official endorsement should be inferred.

References

Arguedas, Carmen, Eva Camacho and José Luis Zofío. 2010. Environmental policy instruments: technology adoption incentives with imperfect compliance. *Environmental and Resource Economics.* 47(2): 261-274.

Bento, Antonio, Benjamin Ho, and Mario Ramirez-Basora. 2015. Optimal monitoring and offset prices in voluntary emissions markets. *Resource and Energy Economics* 41: 202-223.

Burtraw, Dallas, Karen Palmer, and Danny Kahn. 2010. A symmetric safety valve. *Energy Policy.* 38(9): 4921–4932.

Bushnell, James B. 2012. The economics of carbon offsets. In *The design and implementation of U.S. climate policy*, ed. Don Fullerton and Catherine Wolfram. 197-209. Chicago, IL: University of Chicago Press.

Caffera, Marcelo, and Carlos A. Chavez. 2011. The cost-effective choice of policy instruments to cap aggregate emissions with costly enforcement. *Environmental and Resource Economics.* 50(4): 531-557.

California Air Resources Board. 2011. *Overview of ARB Emissions Trading Program*. Sacramento CA: California Environmental Protection Agency.

Cason, Tim N., and Lata Gangadharan. 2006. Emissions variability in tradable permit markets with imperfect enforcement and banking. *Journal of Economic Behavior and Organization.* 61(2): 199-216.

Chavez, Carlos A. and John K. Stranlund. 2003. Enforcing transferable permit systems in the presence of market power. *Environmental and Resource Economics.* 25(1): 65-78.

Chevallier, Julien. 2012. Banking and borrowing in the EU ETS: a review of economic modelling, current provisions and prospects for future design. *Journal of Economic Surveys* 26(1): 157-176.

Cohen, Mark. 1999. Monitoring and enforcement of environmental policy. In *International yearbook of environmental and resource economics 1999/2000,* ed. Tom Tietenberg and Henk Folmer. 44–106. Northampton, MA: Edward Elgar Publishing.

Deveny, Adrian, Janet Nackoney, Nigel Purvis, Mykola Gusti, Raymond J. Kopp, Erin Myers Madeira, Andrew R Stevenson, Georg Kindermann, Molly K. Macauley and Michael Obersteiner. 2009. *Forest carbon index: the geography of forests in climate solutions.* Washington DC: Resources for the Future.

Earnhart, Dietrich. 2009. The influence of facility characteristics and permit conditions on the effectiveness of environmental regulatory deterrence. *Journal of Regulatory Economics.* 36(3): 247-273.

Ellerman, A. Denny, and Juan Pablo Montero. 2007. Efficiency and robustness of allowance banking in the U.S. Acid Rain Program. *The Energy Journal* 28(4): 47-71.

European Environment Agency. 2008. *Application of the Emissions Trading Directive by EU Member States – Reporting Year 2008*. Copenhagen: European Environment Agency.

Fisher-Vanden, Karen, and Sheila Olmstead. 2013. Moving pollution trading from air to water: potential, problems, and prognosis. *Journal of Economic Perspectives* 27(1): 147-171.

Friesen, Lana, and Lata Gangadharan. 2013. Environmental markets: what do you learn from the lab? *Journal of Economic Surveys.* 27(3): 515-535.

Garvie, Devon, and Andrew Keeler. 1994. Incomplete enforcement with endogenous regulatory choice. *Journal of Public Economics.* 55(1): 141-162.

Gray, Wayne, and Ronald Shadbegian. 2005. When and why do firms comply? Paper mills in the 1980's. *Law and Policy.* 27(2): 238-261.

Gray, Wayne, and Ronald Shadbegian. 2007. The environmental performance of polluting plants: a spatial analysis. *Journal of Regional Science.* 47(1): 63-84.

Gray, Wayne, and Jay P. Shimshack. 2011. The effectiveness of environmental monitoring and enforcement: a review of the empirical evidence. *Review of Environmental Economics and Policy.* 5(1): 3-24.

Hahn, Robert. 1984. Market power and transferable property rights. *Quarterly Journal of Economics.* 99(4): 735-765.

Helm, Carsten. 2003. International emissions trading with endogenous allowance choices. *Journal of Public Economics.* 87(12): 2737-2747.

Heyes, Anthony. 2000. Implementing environmental regulation: enforcement and compliance. *Journal of Regulatory Economics.* 17(2): 107-29.

Hood, Christina. 2010. *Reviewing existing and proposed emissions trading systems*. Paris: International Energy Agency.

Hung, Ming-Feng, and Daigee Shaw. 2005. A trading-ratio system for trading water pollution discharge permits. *Journal of Environmental Economics and Management* 49(1): 83-102.

Innes, Robert. 2001. Self-enforcement of environmental law. In *The law and economics of the environment*, ed. Anthony Heyes. 150-184. Northampton MA: Edward Elgar Publishing.

Innes, Robert. 2003. Stochastic pollution, costly sanctions, and optimality of emission permit banking. *Journal of Environmental Economics and Management.* 45(3): 546-68.

Interpol. 2013. *Guide to Carbon Trading Crime*. http://www.interpol.int/en/Media/Files/Crime-areas/Environmental-crime/Guide-to-Carbon-Trading-Crime-2013. (Last accessed May 17, 2016).

Jacoby, Henry D. and A. Denny Ellerman. 2004. The safety valve and climate policy. *Energy Policy.* 32(4): 481-491.

Jaffe, Judson, Matthew Ranson and Robert N. Stavins. 2009. Linking tradable permit systems: a key element of emerging international climate policy architecture. *Ecology Law Quarterly.* 36(4): 789-808.

Kruger, Joseph, Wallace E. Oates, and William A. Pizer (2007). Decentralization in the EU Emissions Trading Scheme and lessons for global policy. *Review of Environmental Economics and Policy.* 1(1): 112-133.

Keeler, Andrew. 1991. Noncompliant firms in transferable discharge permit markets: Some extensions. *Journal of Environmental Economics and Management.* 21(2): 180-189.

Malik, Arun S. 1990. Markets for pollution control when firms are noncompliant. *Journal of Environmental Economics and Management.* 18(2): 97-106.

Malik, Arun S. 1992. Enforcement costs and the choice of policy instruments for controlling pollution. *Economic Inquiry.* 30(4): 714-721.

Malik, Arun S. 2002. Further results on permit markets with market power and cheating, *Journal of Environmental Economics and Management.* 44(3): 371-390.

McAllister, Lesley. 2010. The enforcement challenge of cap-and-trade regulation. *Environmental Law*. 40(4): 1195-1230.

Metcalf, Gilbert E. and David Weisbach. 2012. Linking policies when tastes differ: global climate policy in a heterogeneous world. *Review of Environmental Economics and Policy*. 6(1): 110-129.

Montero, Juan-Pablo. 2002. Prices versus quantities with incomplete enforcement. *Journal of Public Economics.* 85(3): 435-454.

Montero, Juan-Pablo, Jose Miguel Sanchez, and Ricardo Katz. 2002. A market-based environmental policy experiment in Chile. *Journal of Law and Economics.* 45(1): 267-287.

Muller, Nicholas Z., and Robert Mendelsohn. 2009. Efficient pollution regulation: getting the prices right. *American Economic Review* 99(5): 1714-1739.

Murphy, James J. and John K. Stranlund. 2006. Direct and indirect effects of enforcing emissions trading programs: An experimental analysis. *Journal of Economic Behavior and Organization.* 61(2): 217-233.

Murphy, James J. and John K. Stranlund. 2007. A laboratory investigation of compliance behavior under tradable emissions rights: Implications for targeted enforcement. *Journal of Environmental Economics and Management.* 53(2): 196-212.

Newell, Richard G., William A. Pizer, and Daniel Raimi. 2013. Carbon markets 15 years after Kyoto: lessons learned, new challenges. *Journal of Economic Perspectives.* 27(1): 123–146.

Palacios, Milagro and Carlos A. Chávez. 2005. Determinants of compliance in the emissions compensation program in Santiago, Chile. *Environment and Development Economics.* 10(4): 453-483.

Pizer, William A. 2002. Combining price and quantity controls to mitigate global climate change. *Journal of Public Economics.* 85(3): 409-434.

Roberts, Marc J. and Michael Spence. 1976. Effluent charges and licenses under uncertainty. *Journal of Public Economics.* 5(3-4): 193-208.

Rubin, Jonathan. 1996. A model of intertemporal emissions trading, banking, and borrowing. *Journal of Environmental Economics and Management.* 31(3): 269-286.

Shimshack, Jay P. 2014. The economics of environmental monitoring and enforcement. *Annual Review of Resource Economics.* 6(1): 339-360.

Sigman, Hilary, and Howard F. Chang. 2011. The effect of allowing pollution offsets with imperfect enforcement. *American Economic Review Papers and Proceedings.* 101(3): 268–272.

Stavins, Robert. 1995. Transactions costs and tradeable permits. *Journal of Environmental Economics and Management.* 29(2): 133-148.

Stavins, Robert. 1998. What can we learn from the grand policy experiment? Lessons from SO 2 allowance trading. *Journal of Economic Perspectives* 12(3): 69-88.

Stavins, Robert. 2008. Addressing climate change with a comprehensive US cap-and-trade system. *Oxford Review of Economic Policy.* 24(2): 298-321.

Stranlund, John K. and Kathy K. Dhanda. 1999. Endogenous monitoring and enforcement of a transferable emissions permit system. *Journal of Environmental Economics and Management.* 38(3): 267-282.

Stranlund, John K., Christopher Costello, and Carlos A. Chavez. 2005. Enforcing emissions trading when emissions permits are bankable. *Journal of Regulatory Economics* 28(2): 181-204.

Stranlund, John K. 2007. The regulatory choice of noncompliance in emissions trading programs. *Environmental and Resource Economics.* 38(1): 99-117.

Stranlund, John K.; Carlos A. Chavez, and Mauricio G. Villena. 2009. The optimal pricing of pollution when enforcement is costly. *Journal of Environmental Economics and Management.* 58(2): 183–191.

Stranlund, John K., James J. Murphy and John M. Spraggon. 2011. An experimental analysis of compliance in dynamic emissions markets. *Journal of Environmental Economics and Management.* 62(3): 414-429.

Stranlund, John K., James J. Murphy and John M. Spraggon. 2013. Imperfect enforcement of emissions trading and industry welfare: a laboratory investigation. In *Handbook on Experimental Economics and the Environment*, ed. John List and Michael Price. 265-288. Northampton MA: Edward Elgar Publishing.

Stranlund, John K. and L. Joe Moffitt. 2014. Enforcement and price controls in emissions trading. *Journal of Environmental Economics and Management.* 67(1): 20-38.

Tietenberg, Tom H. 2006. *Emissions Trading: Principles and Practice*. 2nd ed. Washington DC: Resources for the Future.

US Congress. 2009. American clean energy and security act of 2009. H.R. 2454, 111th Congress.

US Environmental Protection Agency. 2003. *Section-by-section summary of the Clear Skies Act of 2003*. http://archive.epa.gov/clearskies/web/pdf/csa2003sectionbysection_2_27_03_final.pdf. (Last accessed August 18, 2015)

US Environmental Protection Agency. 2009. *NO_X Budget Trading Program: 2008 highlights.* Washington DC: US Environmental Protection Agency Clear Air Markets Division.

US Environmental Protection Agency. 2010. *Acid rain and related programs 2009 highlights: 15 years of results 1995 to 2009.* Washington DC: US Environmental Protection Agency Clear Air Markets

van Egteren, Henry and Mariane Weber. 1996. Marketable permits, market power, and cheating. *Journal of Environmental Economics and Management.* 30(2): 161-173.

Villegas-Palacios, Clara and Jessica Coria. 2010. On the interaction between imperfect compliance and technology adoption: taxes vs. tradable emissions permits. *Journal of Regulatory Economics.* 38(3): 274-291.

Weitzman, Martin L. 1974. Prices vs. quantities. *Review of Economic Studies.* 41(4): 477-91.

Zhang, Zhong Xiang. 2015. Carbon emissions trading in China: the evolution from pilots to a nationwide scheme. *Climate Policy*. 15(sup1): S104-S126.