Universidad de
los Andes
Facultad de Administración

CÁTEDRA CORONA 20

The Economics of Enforcing Market-Based Pollution Control

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Foreword

The Corona Visiting Scholars publishing program is the editorial byproduct of presentations by internationally recognized foreign scholars who visit the Management School of the Universidad de los Andes for a brief period thanks to funds donated by the Corona Organization in 1996 to finance the visiting scholar program that bears its name.

Through the years, the Corona Distinguished Visitors Program has fostered valuable exchange among researchers and teachers, renewing and stimulating the School's academic environment. It has also strengthened links with the international academic community in various areas of management and produced valuable feedback about the School's orientation, problems and future plans.

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The program also promotes travel by the School's academic staff to foreign academic institutions to strengthen *the School's strategic connections and create long-term relationships with academic peers in foreign institutions.*

With more than 160 visitors coming from various North American, European, Asian, Australian and Latin American universities in the United States, France, England, Spain, China, India, Australia, Argentia, Brazil, Mexico and Venezuela, this series of publications is editorial testimony of the program's valuable contribution. The current issue, number 20 in a series, contain a paper written by John Stranlund, Professor of Environmental and Resource Economics in the Department of Resource Economics at the University of Massachusetts, Amherst, during his visit in April 2011.

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Introduction

Emission trading programs (also referred to as transferable or tradable pollution rights, and cap-and-trade) are quite simple, yet have very powerful implications. By exploiting the power of a market to allocate pollution control responsibilities and by freeing facilities to choose the cheapest way to reduce their emissions, well-designed trading programs promise to achieve environmental quality goals more cheaply than traditional command-and-control regulations. Despite the advantages of market-based environmental policies over traditional command-and control approaches, these programs are not likely to perform as expected if they are not enforced well. Recognizing this, there is now a significant body of literature on the economics of compliance and enforcement in emissions trading programs. This paper reviews this literature and draws lessons from it for designing markets to control greenhouse gas emissions.

The economics of the enforcement problem in cap-and-trade has developed as these programs have been implemented around the world. Perhaps the most intensely studied cap-and-trade program is the U.S. SO_2 Allowance Trading Program, which controls sulfur dioxide emissions from U.S. electric power plants. Another successful U.S. cap-and-trade program was the NO_X Budget Trading Program, which was designed to control summer ozone concentrations in northeastern states. More local programs have also been implemented. For example, the Regional Clean Air Incentives Market (RECLAIM) controls NO_X and SO_X emissions from stationary sources in southern California while Santiago, Chile's Emissions Compensation Program controls total suspended particulates in the city. The largest cap-and-trade program is the European Union's Emissions Trading Scheme (EU ETS), which controls the CO_2 emissions from 11,500 sources. These are only a few of the existing emissions trading programs and many others have been proposed. In particular, new greenhouse gas control policies usually focus on cap-and-trade programs.

The fundamental structure of a cap-and-trade program involves a cap on aggregate emissions of a particular pollutant from a specified set of sources. The cap is often tightened over time. In every compliance period (often one year's duration), emissions permits (also called allowances or credits) consistent with the cap are allocated to the sources. Each permit confers the legal right to release a unit of pollution. Sources may apply these permits to their emissions in the current compliance period, sell excess permits to other pollution sources, or purchase permits from other firms if their emissions exceed their permit holdings. Most programs allow sources to save permits for use or sale in future compliance periods, and some programs allow firms to borrow permits from future permit allocations.

The fundamental problem of enforcing cap-and-trade programs is to make sure that pollution sources hold enough permits to cover their current emissions. This requires that regulators have systems in place to track emissions permits so that they know how many permits a source holds at any point in time. The much more difficult problem, however, is to monitor emissions produced by sources. This can be done directly through the use of continuous emissions monitoring systems, which measure the continuous flow of pollution leaving a facility. A cheaper alternative is to allow firms to estimate their emissions using specific formulae and procedures. As with most environmental law, existing and proposed cap-and-trade programs rely heavily on self-monitoring and self-reporting of data used to determine compliance. This data includes emissions or estimated emissions and the data used for the estimates, as well as quality assurance and quality control information related to the operation of monitoring technologies. Comparing a firm's permit holdings to its emissions (or estimated emissions) for a compliance period determines whether it is violating its permits, and a source that has excess emissions typically faces a financial penalty and a reduction in its permit allocation in the next period. In addition, sanctions for misreporting of emissions and other data must be in place to deter reporting violations.

The economic literature on enforcing cap-and-trade programs starts with theory that combines the cost to pollution sources of controlling their emissions, imperfect monitoring of emissions, and sanctions for excess emissions. This theory was first used to develop positive results about firms' compliance choices under these programs, highlighting the important role that permit prices have in determining compliance choices. This has several consequences; one of the most important being that under cap-and-trade individual compliance choices are linked together, whereas compliance decisions under other policies (e.g., command-and-control standards or emissions taxes) are largely independent. Thus, analyses of compliance decisions must examine individual compliance decisions and how these decision impact and are impacted by the workings of the emissions permit market. The next section of the paper examines a simple model of source compliance and market performance under cap-and-trade to demonstrate fundamental theoretical results that have been identified in the literature.

Unfortunately there are limited empirical investigations of compliance behavior and the performance of actual emissions markets under different enforcement regimes, largely because of the lack of appropriate field data. In situations in which field data are limited, laboratory experiments can provide valuable information, and several authors have used these experiments to test hypotheses related to compliance in cap-and-trade programs. Consequently, all of the empirical tests of hypotheses concerning compliance under cap-and-trade programs now available come from laboratory experiments. These tests, which are reviewed throughout the paper, tend to support theoretical models of compliance in emissions markets.

Positive theoretical and experimental results about individual compliance decisions and market performance have been used to draw normative conclusions about efficient enforcement strategies — that is, levels of monitoring and sanctions for permit and reporting violations. Some of this literature has looked at efficient enforcement given that the other components of a trading policy have already been determined. In principle, however, the enforcement component of a cap-and-trade policy should be determined simultaneously with all its other elements. Thus, some authors have developed theoretical insights into the efficient design of cap-and-trade policies with their enforcement provisions. The main lesson from this literature is that an efficient cap-and-trade policy will typically include enforcement provisions designed to motivate full compliance by pollution sources.

Cap-and-trade programs are fundamentally dynamic. Overall emissions caps tend to evolve over time, abatement investments can be long-lived, and most programs allow sources to trade emissions permits across time by saving them for the future, and sometimes allowing sources to borrow against future allocations. The article examines theoretical and experimental results concerning the compliance and enforcement problem in dynamic cap-and-trade programs. This literature highlights the critical role that self-reporting of emissions plays in dynamic trading programs with imperfect emissions monitoring.

While cap-and-trade programs can and have been used to control a variety of pollutants, much of the current focus is on their use to control greenhouse gas emissions that contribute to global climate change. The paper concludes by using results from the previous sections to draw lessons about enforcement and compliance in international markets for greenhouse gas control. The focus is on three elements of these markets, first examining lessons for compliance monitoring and the setting of sanctions in greenhouse gas cap-and-trade programs. Second, it is likely that greenhouse gas control in the medium term will consist of many independent national and regional cap-and-trade programs instead of a single global program. Linking programs together so that sources under one program can trade permits with sources in other programs is an important concern. The article therefore examines some of the compliance and enforcement consequences of linking cap-and-trade programs. Finally, most programs for greenhouse gas control allow the use of offsets that are generated by abatement activities outside the program. Consequently, the article examines some of the monitoring and enforcement issues related to offset provisions in cap-and-trade policies.

I. Firm behavior and market equilibrium under cap-and-trade

This section begins with a model of firm behavior and the market equilibrium of an emissions trading policy when firms may be noncompliant. The model in this section is a simple static one that allows a focus on fundamental behavioral and market results. Following presentation of the theoretical results, the experimental evidence that tests some of these results is reviewed.

I.I. A simple model of compliance under cap-and-trade

Consider a fixed set of heterogeneous risk neutral firms. Firm *i*'s gross profit from emitting q_i is given by the strictly concave gross profit function $b_i(q_i)$[1]. Absent a regulatory motivation to reduce its emissions, the firm emits $\bar{q}_i$, the solution to $b_i'(q_i) = 0$. A market for emission permits will generate a permit price that motivates the firm to emit $q_i < \bar{q}_i$. For these levels of emissions, $b_i'(q_i) > 0$. A total of $L < \sum \bar{q}_i$ emissions permits are distributed to the firms free of charge. Firm *i*'s initial allocation is l_i^0, and it chooses to hold l_i permits after trading is completed. Each permit confers the legal right to emit one unit of emissions. Assume competitive behavior

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[1] Strictly speaking, $b_i(q_i)$ is the firm's gross profit assuming that it makes all of its input and output choices optimally. See Montgomery (1972) for a demonstration of the concavity of profit in emissions for firms that are price-takers in input and output markets. Many authors choose to model firms' abatement costs rather than profits from emissions. The approaches are equivalent.

in the permit market so that all trades take place at a constant price p.

In this simple model a firm is noncompliant if its emissions exceed the number of permits it holds and the magnitude of its violation is $v_i = q_i - l_i > 0$. If the firm is compliant, $q_i - l_i \leq 0$ and $v_i = 0$. The regulator maintains a registry that tracks permit allocations and permit trades, so that at any point in time the regulator has perfect information about how many permits each firm holds.

The much more difficult problem, however, is how to monitor sources' emissions. This can be done directly with the use of continuous emissions monitoring systems. The largest pollution sources in the SO_2 Trading Program and RECLAIM are required to install these systems. Since the systems are expensive to install and maintain, an alternative is to allow sources to estimate their emissions. Smaller sources in the SO_2 Trading Program and RECLAIM, as well as nearly all sources in the EU ETS, estimate their emissions rather than monitor them directly. Estimates tend to be based on formulae 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). To keep compliance monitoring as simple as possible suppose that a firm i's emissions are monitored imperfectly with a known and fixed probability π_i. At this stage, allow this monitoring probability to vary across firms.

The failure of sources to hold sufficient permits to cover their emissions must be penalized in order to deter these violations. Some programs penalize permit violations with a fixed per-unit financial penalty. For example, in the U.S. SO_2 Allowance Trading program the penalty for failing to hold enough permits was set at $2,000 per ton of excess emissions in 1990, and is adjusted for inflation every year. In the 2009 compliance year the penalty was $3,517 (U.S. EPA 2010). In addition, noncompliant firms must offset permit violations with a reduction in the permit allocation in the next period. Similarly, the EU ETS set a permit violation penalty of €40 per ton of excess CO_2-equivalent emissions during the program's trial period (2005-2007), which increased to €100 per ton in the second phase, 2008-2012. Excess emissions must also be offset in the following year (European Commission 2003, Article 16). Other programs use alternative sanctions. For example, in the EPA's NO_X Budget Trading Program permit violations were penalized with an offset from the following year's permit allocation on a three-to-one basis (U.S. EPA 2009). The recently proposed American Clean Energy and Security Act of 2009 (U.S. Congress 2009) includes a permit violation penalty that is set at twice the market value of CO_2 permits during a compliance year. For modeling purposes, suppose that a firm that is found to be in violation faces a financial sanction that is summarized by the penalty function, $f(v_i)$, which is strictly increasing and convex for $v_i \geq 0$.

Assuming that each firm chooses positive emissions and holds a positive number of permits, firm *i*'s objective is:

$$\max_{q_i, l_i} b_i(q_i) - p(l_i - l_i^0) - \pi_i f(q_i - l_i) \quad \text{subject to } q_i - l_i \geq 0. \qquad [1]$$

Restricting the firm to $v_i = q_i - l_i \geq 0$ follows from the fact that a firm will never have an incentive to be over-compliant in this static environment. Letting $\mathcal{L}$ denote the Lagrange equation for [1] and λ_i denote the multiplier attached to the constraint, the first-order conditions for a solution to [1] are:

$$\mathcal{L}_q = b_i'(q_i) - \pi_i f'(q_i - l_i) + \lambda_i = 0; \qquad [2]$$

$$\mathcal{L}_l = -p + \pi_i f'(q_i - l_i) - \lambda_i = 0; \qquad [3]$$

$$\mathcal{L}_\lambda = q_i - l_i \geq 0,\ \lambda_i \geq 0,\ \lambda_i(q_i - l_i) = 0. \qquad [4]$$

Because the constraint $q_i - l_i \geq 0$ is linear and the firm's objective is strictly concave these conditions are necessary and sufficient to identify unique optimal choices of emissions, permit demand, and violation level.

It is straightforward to use [2] through [4] to show that a firm under an emission trading program is compliant if only if $p \leq \pi_i f'(0)$; that is, a firm holds enough permits to cover its emissions if and only if the prevailing permit price is not less than the expected marginal penalty of a slight violation. Moreover, a firm that violates its permits chooses the level of violation according to $p = \pi_i f'(v_i)$. It is straightforward to demonstrate that a firm's violation increases with the permit price and decreases with higher monitoring and penalties. It is important to note that a firm's permit compliance decision depends on the permit price and the enforcement strategy all firms face, but it does not depend on anything that is unique about the firm. What drives this result is the ability of a permit market to equate the marginal incentives of risk-neutral firms to release emissions and to violate their permits.

For this reason, Stranlund and Dhanda (1999) argue that the differences in the size of individual violations of risk-neutral firms that trade permits competitively should be independent of differences in their benefits from emissions and their initial permit allocations. Conceptually, there is no reason for regulators to believe that some firms will be more likely to be noncompliant or tend toward higher violations even though they may have different abatement or production technologies, or initial permit allocations. Hence, a regulator who is motivated to target enforcement resources to detect incidences of noncompliance or higher levels of violation cannot do so productively on the basis of firm-level characteristics. Moreover, suppose that a budget-constrained regulator seeks to distribute their enforcement effort to minimize aggregate violations. (For a uniformly mixed pollutant, this is equivalent to minimizing the environmental harm from noncompliance). Since a firm's choice of violation is independent of its benefits from emissions and its initial allocation of permits, the distribution of the marginal productivities of enforcement effort across firms is independent of these parameters as well. Thus, a regulator that seeks to minimize the aggregate violations of firms cannot use differences among them to target its monitoring effort.

In particular, this implies that regulators do not need to monitor some sources more closely than others. In terms of modeling, this result may be used to make monitoring probabilities equal for all sources. That is, assume $\pi_i = \pi$ for each source *i*.

Matters are very different for firms that face command-and-control standards. A risk-neutral firm's decision about whether to comply with a fixed emissions standard is determined by the relationship between its marginal benefit from increased emissions and the marginal expected penalty it faces for violating the standard. Consequently, firms with higher marginal benefits of emissions or who face stricter standards will have a greater incentive to be noncompliant. In this way, firm-level characteristics are important determinants of compliance with fixed standards (Garvie and Keeler 1994). Gray and Shadbegian (2005) find support for this conclusion in their analysis of compliance behavior by pulp and paper manufacturers in the U.S.. Since the characteristics of firms partly determine their compliance choices when they face emissions standards, authorities can productively condition the distribution of enforcement effort on firms' characteristics to achieve compliance goals. Conceptually, this would not be productive under a competitive cap-and-trade program.

Turning now to firms' choices of emissions, combine equations [2] and [3] to obtain $p = b_i'(q_i)$. This is the familiar rule that competitive firms will choose their emissions to equate the going permit price to their marginal benefits of increased emissions. Note that a firm's choice of emissions does not depend directly on the enforcement strategy it faces. Enforcement can have an indirect effect on firms' emissions as it affects the price of permits, but individual firms' emissions choices are independent of enforcement.

This has an important consequence for the performance of emissions markets when firms may be noncompliant. Under reasonable specifications of the monitoring probability, Malik (1990) demonstrated that a competitive permit market will distribute individual emissions-control responsibilities so that, regardless of the level of aggregate abatement actually achieved, aggregate abatement costs are minimized. Moreover, Malik showed that this result does not depend on the firms' risk preferences. Malik's result is fully equivalent to saying that aggregate gross profit will be maximized given the actual level of aggregate emissions despite imperfect enforcement and noncompliance. This conclusion derives from the result that each firm chooses its emissions so that $p = b_i'(q_i)$. This decision rule equates marginal gross profits across firms, which provides the necessary conditions for maximizing industry gross profit given some level of aggregate emissions. Thus, letting Q denote aggregate emissions, in a market equilibrium we have:

$$p = B'(Q), \text{ where } B(Q) = \max_{q_i} \sum_{i=1}^{n} b_i(q_i) \quad \text{s.t.} \quad \sum_{i=1}^{n} q_i = Q. \qquad [5]$$

Since the ability of the permit market to allocate individual emissions choices efficiently is not necessarily affected by the enforcement strategy that is applied to the market, the main effect of the imperfect enforcement of emissions trading programs is that aggregate emissions will exceed the aggregate supply of emissions permits.

Just as equating the firms' marginal incentives to pollute maximizes aggregate gross profit given aggregate emissions, equating the marginal violation incentives of risk-neutral firms minimizes aggregate expected penalties given aggregate emissions. Given Q, and a supply of permits L, aggregate violations are $V = Q - L$. Obviously, V must be greater than or equal to zero. It is straightforward to show that in a permit equilibrium with $V > 0$,

$$p = P'(V), \text{ where } P(V) = \min_{v_i} \sum_{i=1}^{n} \pi f(v_i) \quad \text{s.t.} \quad \sum_{i=1}^{n} v_i = V. \qquad [6]$$

That is, $P(V)$ is minimum aggregate expected penalties for aggregate violations V, and in equilibrium the permit price is equal to the marginal of this function, which is weakly increasing in V.

Combining [5] and [6] while accounting for the possibility of full compliance identifies the equilibrium permit price and aggregate emissions:

1. If $B'(L) \leq P'(0)$, then $Q = L$ and $p = B'(L)$.
2. If $B'(L) > P'(0)$, then $Q > L$ and $p = B'(Q) = P'(Q - L)$.

These conditions are interpreted in the following way. In the first case, the aggregate marginal expected penalty does not fall below the price of permits, which implies that all firms are compliant. The permit price is then equal to the aggregate marginal gross profit at the supply of permits. In the second case, the aggregate marginal expected penalty is less than aggregate marginal gross profit at the supply of permits. This results in aggregate noncompliance and the equilibrium price and aggregate emissions are determined by the three-way equality between the permit price, aggregate marginal gross profit, and the aggregate marginal expected penalty.

The equilibrium comparative statics of the problem when enforcement does not ensure full compliance are easy to demonstrate (see Stranlund and Dhanda 1999). Aggregate emissions and violations increase as enforcement is weakened, either by reducing the monitoring probability or reducing the marginal penalty function. Because weaker enforcement decreases the aggregate demand for permits, the equilibrium permit price falls. Increasing the supply of permits decreases the equilibrium permit price and increases aggregate emissions, but aggregate violations fall.

1.2. Experimental tests of the basic model

As noted in the introduction, opportunities for testing hypotheses about compliance in cap-and-trade programs with field data are severely limited. Many existing programs have achieved such high rates of compliance that there is not enough variation in compliance choices to conduct meaningful statistical analyses (e.g. the SO_2 Allowance Trading and NO_X Budget Programs; EU ETS). Moreover, there are almost no analyses of compliance behavior in programs that have had significant noncompliance (e.g., RECLAIM; Santiago's Emissions Compensation Program)[2]. Consequently, empirical tests of these hypotheses have been limited to tests with data generated in laboratory environments. While econometric studies using field data are critical for understanding the effectiveness of existing policies, data limitations and the inability to vary these policies in a controlled setting can preclude direct tests of theoretical predictions. Moreover, experiments provide direct control over the parameters of interest, allowing researchers to perform sensitivity analyses that may not be possible outside the laboratory[3].

The most complete set of such tests is provided in Murphy and Stranlund (2006 and 2007) and Stranlund, Murphy and Spraggon (2009). As is typical of experiments, subjects were placed in a neutral environment to avoid introducing potential biases due to individual attitudes about the environment or cap-and-trade. During each period of the experiment, eight subjects simultaneously chose to produce units of a fictitious good and traded in a market for permits that conveyed the right to produce. Four subjects in each group had a high marginal benefit from the production schedule, while the other four had a lower marginal benefit function. At the end of the period, each individual was audited with a known, exogenous probability. If an individual was audited and found to be non-compliant (i.e., total production exceeded permit holdings), then a penalty was applied that was generated from a strictly convex penalty function. Four enforcement strategies were developed by changing the monitoring probability and penalty function. Other treatment effects in the experiments involved the free initial allocation of permits. There were two levels of

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[2] The only exception is Palacios and Chávez (2005) who examined compliance decisions in Santiago's trading program. So few trades had taken place at the time of their analysis that the program functioned more like a system of emissions standards than tradable emissions permits. Their findings, therefore, may have limited applicability to fully functioning trading programs.

[3] Although experimental techniques have been used to evaluate other policy initiatives, including some aspects of emissions trading programs, these techniques have not yet been widely applied to issues of regulatory enforcement. The bulk of experimental analyses of compliance and enforcement are in the area of income tax compliance. See Alm and McKee (1998) and Torgler (2002) for comprehensive surveys of this literature.

the aggregate permit supply, and for the higher permit supply there were two distributions of individual initial allocations.

Murphy and Stranlund (2006) focused on the hypotheses associated with the idea that changes in enforcement can have direct effects on compliance choices as well as indirect effects that occur via changes in the permit price. Increased enforcement motivates firms to reduce their violations by purchasing more permits. This is the direct effect on compliance of enforcement. The higher demand for permits puts upward pressure on the equilibrium permit price, but higher permit prices motivate firms toward greater violations. This is the indirect effect of increased enforcement on compliance that works in the opposite direction to the direct effect. Theoretically, the direct effect always outweighs the indirect effect so that greater enforcement produces greater compliance, but regulators need to be aware that the productivity of enforcement pressure in reducing noncompliance in emissions trading programs is partially offset by a countervailing price effect. In terms of individual emissions, recall that theory suggests that individual emissions are independent of enforcement strategies but decrease as permit prices increase. Thus, the direct effect of increased enforcement on individual emissions is zero; there is only a negative indirect effect.

The experimental data are consistent with this set of predictions. Murphy and Stranlund (2006) confirmed the hypotheses that individual violations increase in the permit price while individual emissions decrease. In the experiments, more vigorous enforcement (either increased monitoring or penalties) reduced individual violation levels directly. However, increased enforcement also produced higher permit prices, which led to higher individual violations. Consistent with theoretical predictions, the direct effect of increased enforcement outweighed the indirect effect. Murphy and Stranlund (2006) also confirmed the hypotheses that there is no direct effect of increased enforcement on individual emissions, only a negative indirect effect.

Murphy and Stranlund (2007) focused on testing theoretical results related to the impacts of source characteristics on compliance decisions. Recall that a source's violation decision is, in theory, determined simply by the going permit price and the expected marginal penalty. Since neither of these depend on source characteristics such as their gross profit functions or their initial allocations of permits, their violation choices will be independent of these characteristics as well. This result has an important policy implication, because it suggests that regulators have no reason to target enforcement effort based on individual source characteristics. Murphy and Stranlund (2007) confirmed that individual violations are independent of differences in subjects' marginal benefit functions, as predicted. However, individual violations were not independent of the initial allocation of permits. They found that subjects that were predicted to buy permits tended to have higher violation levels than those who were predicted to sell permits. While this suggests that enforcers may be motivated to target permit buyers because they will tend to be more noncompliant than sellers, Murphy and Stranlund (2007) demonstrated that the marginal productivity of increased enforcement in reducing individual violations was independent of differences in both individual emissions benefits and initial permit allocations. Thus, under the important policy objective of maximizing the productivity of scarce enforcement resources, regulators have no theoretical or empirical justification for targeting firms based on their individual characteristics.

To drive the point home, Murphy and Stranlund (2007) conducted experiments that were identical to their market experiments except that subjects could not trade their permit allocations. Thus, these experiments considered subjects' compliance decisions when they faced fixed emissions standards. Consistent with theoretical predictions by Garvie and Keeler (1994), subjects with higher marginal benefits had significantly higher violations and were much more responsive to increased enforcement. Thus, there is substantial justification for pursuing targeted enforcement strategies when firms face fixed emissions standards, but little reason to do so in emissions trading programs.

Stranlund, Murphy and Spraggon (2009) examined the welfare consequences of imperfect enforcement in emissions markets. Recall that Malik (1990) demonstrated that competitive permit markets will distribute individual emissions-control responsibilities so that, regardless of the level of aggregate abatement actually achieved, the aggregate costs of abatement are minimized. Thus, the main problem of imperfect enforcement is that emissions will exceed the cap imposed by the supply of permits. Empirically, Stranlund *et al.* (2009) note that deviations from predictions about industry welfare can be decomposed into two effects. The first is an allocation effect that accounts for deviations in industry profits, given the observed level of aggregate emissions. By isolating this effect the researchers were able to determine whether the laboratory market allocated individual emissions control responsibilities among firms cost-effectively, despite significant permit violations. The second part of the deviations of industry profits from predicted values is a compliance effect that can arise if aggregate emissions and violations differ from predicted values. Note that such a deviation does not indicate a market failure because such deviations can stem from a failure of the standard model to predict compliance choices accurately.

Stranlund *et al.* (2009) found that their experimental permit markets were highly efficient at allocating individual emissions control, despite imperfect enforcement and significant violations. However, aggregate violations and emissions were significantly lower than predicted when these were predicted to be very high, while violations and emissions were quite close to predicted values when they were predicted to be lower. These results suggest that cap-and-trade is a reasonably efficient way to allocate individual emissions control responsibilities, even when enforcement is imperfect. Moreover, poorly enforced programs may not result in as much noncompliance as a standard model would predict. Depending on the benefits of pollution control in a particular setting, lower-than-predicted emissions could result in higher-than-predicted social welfare. This should not be a justification for implementing imperfectly enforced trading programs; it does, however, suggest that imperfect enforcement may not always be as costly as standard models would predict.

That subjects in the Stranlund *et al.* (2009) experiments did not violate their permits as much as theory would suggest is a common result. It has been observed in other settings, including in other emissions trading experiments (e.g., Raymond and Cason 2010), tax compliance experiments (Torgler 2002, Alm and McKee 1998), and tax compliance in the field (Andreoni *et al.* 1998). Despite this consistent finding, researchers have not yet fully explored the different behavioral motivations that drive this phenomenon. This seems to be an important area for future research.

2. Optimal enforcement of cap-and-trade

To this point the focus has been on positive compliance and market results under the assumptions that the parameters of a cap-and-trade program (monitoring, penalties and permit supply) are exogenous. This section turns to the normative issue of determining the optimal trading program in which these elements are jointly set to optimize some social objective.

2.1. Cost-effective enforcement

A key issue in the design of any environmental policy is whether they should be designed to motivate full compliance, or whether permitting a certain amount of noncompliance reduces the costs of reaching environmental quality goals. This problem is rarely addressed in the literature on designing emissions trading programs. Most of the literature simply assumes that regulators do not or cannot apply enough enforcement pressure to induce compliance by sources of pollution. Examples of this approach include Malik (1990, 2002), Keeler (1991), van Egteren and Weber (1996), Stranlund and Dhanda (1999), and Montero (2002). Others restrict their analyses to full-compliance outcomes (Malik 1992, Stranlund and Chavez 2000, Chavez and Stranlund 2003) without justifying this choice from an efficiency standpoint. In practice we find examples of emissions trading programs with significant noncompliance, as well as examples with near-perfect compliance. Montero, Sanchez and Katz (2002) argue that the development of an emissions trading program for total suspended particulates in Santiago, Chile was hampered by weak enforcement and significant noncompliance. McAllister (2010) reports on compliance problems in the RECLAIM program. On the other hand, several EPA emissions trading programs like the SO_2 Allowance Trading and the NO_X Budget Trading programs have achieved very high rates of compliance (U.S. EPA 2009, 2010).

Some authors assume that enforcement resources are insufficient to induce full compliance. For example, Stranlund and Dhanda (1999) examine the choice of enforcement strategy by an enforcer with an exogenously-constrained budget that is not large enough for the enforcer to achieve full compliance[4]. While limited enforcement resources are certainly a factor in many real instances of environmental policy enforcement, an enforcer's budget is an endogenous element in the determination of an optimal cap-and-trade policy. Another common assumption that is used to preclude full compliance outcomes in the literature is that penalties are restricted not to exceed some maximum level. For example, Montero (2002) assumes that unit penalties cannot be set above permit prices. This assumption is overly restrictive and is not a characteristic of real emissions trading schemes.

Stranlund (2007) has addressed the problem of determining the optimal emission trading program, in particular the optimal level of noncompliance in such a program. In his model a regulator chooses a supply of emissions permits and monitoring to minimize the expected costs of inducing a fixed aggregate emissions target. The expected costs of an emissions trading program include not only the firms' aggregate abatement costs (the reduction in firms' aggregate gross profits as in the previous section) and the government's monitoring costs, but also the expected costs of penalizing noncompliant firms. The expected costs of sanctions have largely been ignored in the literature on enforcing emissions trading policies[5]. In reality, however, penalizing firms is likely to be

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[4] Garvie and Keeler (1994) assume this objective in their analysis of enforcing emissions standards, and Macho-Stadler and Perez-Castrillo (2006) assume the same in their analysis of enforcing emissions taxes.

[5] Modeling costly sanctions is not common in the literature on enforcing environmental policies, but see Malik (1993) and Arguedas (2008) for exceptions. Costly sanctions are also not very common in the much larger

costly. Sanction costs include the administrative costs associated with imposing and collecting penalties. These costs could also include the potentially more substantial costs of government investigative efforts, of firms' efforts to challenge or avoid the imposition of penalties, and government expenditures on fighting off such challenges. Avoiding these costs is a powerful reason to design emissions trading policies in order to achieve full compliance.

In fact, Stranlund (2007) demonstrates that in any static emissions trading scheme that achieves an aggregate emissions target 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 key to this result is recognizing that motivating full compliance eliminates variable penalization costs, and that there are sufficient levers in the design of a trading program (permit supply, monitoring, and penalty function) to achieve any level of aggregate emissions with full compliance, without expending additional monitoring efforts or setting higher marginal penalties. This full-compliance result extends to choosing an efficient emissions trading policy directly if firms' gross profit functions are known with certainty. The reason is that 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 amount of noncompliance is more complicated when firm's abatement costs are uncertain.

2.2. Uncertainty about firm's abatement costs

Policy design under uncertainty about firm's costs of controlling emissions has pre-occupied environmental economists for many decades. Weitzman's (1974) derivation of rules to determine when a quantity policy, such as emissions trading, produces higher social welfare than a price policy such as an emissions tax, continues to be relevant in today's pollution control debates. For example, given the choice

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literature on optimal law enforcement. Polinsky and Shavell (1992) is an exception in this literature.

between a cap-and-trade policy for controlling greenhouse gas emissions and a greenhouse gas tax, there are important reasons to believe that the tax would be more efficient (Nordhaus 2007). However, Roberts and Spence (1976) demonstrated that a hybrid trading/tax policy would usually outperform either a trading or tax policy alone. For example, a cap-and-trade policy with a price ceiling at which the government offers an unlimited supply of extra permits and a price floor at which the government offers to buy back unused permits will often yield higher levels of social welfare than either a pure trading program or a pure tax.

Interest in hybrid pollution control policies has been intense of late, driven mainly by their proposed use in policies to contain the highly uncertain costs of controlling greenhouse gases[6]. The first proposals only involved price ceilings for emissions trading (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 supply of emissions permits in case their abatement costs turn out to be significantly higher than expected. However, adding a price floor along with a price ceiling can improve efficiency by motivating firms to abate below the permit supply cap if their abatement costs turn out to be lower than expected. Several recent simulation studies demonstrate the cost-effectiveness of combining price ceilings and price floors (Burtraw. Palmer and Kahn 2010, Fell and Morgenstern 2010, Philibert 2008)[7].

Several authors have noted that enforcement parameters can be used to provide a price ceiling in emission markets to limit high-side price risk. Some view the relatively high penalties for permit violations in the U.S. SO_2 Allowance Trading program and the EU ETS as safety valves because they place a ceiling on the price of emissions permits in these programs (Jacoby and Ellerman 2004; Stavins 2008). More rigorously, Montero (2002) reexamined the prices

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[6] In fact, emissions trading programs may be particularly susceptible to high permit price volatility (Nordhaus 2007).

[7] Very recent theoretical literature that examines cap-and-trade policies with price controls and other cost-containment measures include Weber and Neuhoff (2010), Webster *et al.* (2010), and Grull and Taschini (2011).

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 compliance tends to favor emissions trading precisely because the expected marginal penalty can provide the price ceiling that improves the efficiency of emissions trading under uncertainty about abatement costs. An expected marginal penalty below what would be necessary to induce full compliance under all circumstances imposes a ceiling on the price of emissions permits. The permit price cannot rise above the expected marginal penalty, because if it did all firms would choose to be noncompliant: they would hold no permits and the market would not clear. If firms′ abatement costs turn out to be very high, the permit price will rise to the expected marginal penalty and firms would increase their emissions beyond a permitted cap by violating their permits. Thus, in the absence of a specific price ceiling, uncertainty about firms′ abatement costs provides a justification for designing emissions trading schemes that may result in imperfect compliance under some realizations of firms′ abatement costs.

While it is possible to design a trading policy that used imperfect enforcement to limit the risk of high abatement costs, there are at least three problems associated with doing so. First, as noted earlier, there are good reasons to avoid dealing with noncompliance. Sanctioning noncompliant firms is not costless, so using imperfect enforcement to provide a safety valve involves the expectation of having to use real resources to levy sanctions on noncompliant firms. Moreover, the public might react negatively to widespread noncompliance in a trading program when it involves higher emissions, encouraging a perception among the public that casts firms as law-breaking polluters. Second, by fixing the expected marginal penalty at some level that provides a price ceiling some outcomes are over-enforced. Suppose that firms′ abatement costs turn out to be at a level that produces a permit price that is strictly lower than the expected marginal penalty, resulting in all firms being compliant. In this case, monitoring could be reduced while still making sure the expected marginal penalty does not fall below the permit price without changing the equilibrium outcome. A third problem with using imperfect enforcement to provide a safety valve is that the policy does not address low-side cost uncertainty; that is, it cannot provide added incentives for firms to reduce their emissions if their abatement costs are significantly lower than expected.

Each of these problems is remedied by a policy that imposes specific price controls for a trading policy and enforces the hybrid policy so that firms are always compliant. This policy eliminates expected penalization costs because firms are always compliant. Moreover, expected monitoring costs can be reduced by tying monitoring efforts to the realization of permit prices. Finally, the policy provides a price floor to motivate additional abatement if abatement costs are lower than expected. Thus, while enforcement can be structured to provide a safety valve for emissions trading, doing so is likely to be an inefficient way to contain uncertain abatement costs.

Stranlund and Moffitt (2011) note another consequence of uncertain abatement costs and the concomitant permit price uncertainty. Since the permit price is the marginal benefit of violating one's permits in an emissions trading program, counteracting the increased incentive toward noncompliance with higher permit prices can make enforcement costs an increasing function of the permit price. Thus, tying monitoring effort to the realization of permit prices can imply that permit price risk is transmitted to enforcement costs. This can be mitigated by conditioning violation penalties on the realization of the permit price. For example, the recently proposed American Clean Energy and Security Act of 2009 (U.S. Congress 2009) includes a permit violation penalty that is set at twice the market value of CO_2 permits during a compliance year. Similarly, the U.S. EPA's proposed (but not enacted) Clear Skies Initiative included a permit violation penalty that was to be set at one- to three-times the clearing price in a recent permit auction (U.S. EPA 2003). In this way, penalties can absorb price variation so that monitoring effort is shielded from price risk. Stranlund and Moffitt show how this simple design feature can improve the efficiency of hybrid emissions trading programs.

3. Dynamic emissions trading

Thus far, results from static models of emissions trading have been discussed. These models are useful for characterizing fundamental aspects of compliance decisions, market responses, and optimal enforcement of emissions trading. However, several aspects of emissions trading make them dynamic. Perhaps the most important is that most cap-and-trade policies allow firms the limited ability to bank emissions permits. For example, the SO_2 Allowance Trading program allows firms to save permits for future use or sale, but does not allow them to borrow against future permit allocations. The U.S. EPA's NO_X Budget Trading Program had similar banking provisions, with the exception that it imposed a heavy discount on saved permits if the aggregate bank reached a specific limit. The newer generation of programs for greenhouse gas emissions tends to allow restricted permit borrowing as well. Examples include the EU ETS and U.S. legislative proposals (e.g., the Low Carbon Economy Act of 2007 (U.S. Congress 2007) and the American Clean Energy and Security Act of 2009 (U.S. Congress 2009)). Banking allows firms to shift abatement across time in a cost-effective manner and to hedge against risks associated with uncertain abatement costs, emissions, and permit prices[8].

Theoretical work by Stranlund, Costello and Chavez (2005) provides results about compliance

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[8] Like price controls, banking provisions can help contain uncertain abatement costs. An interesting paper by Fell and Morgenstern (2010) uses simulations of a U.S. cap-and-trade policy for carbon dioxide to examine the relative contributions of price controls and banking provisions to reducing expected abatement costs. Their results suggest that most of the gain in cost-effectiveness of a trading program with banking (and limited borrowing) and price controls is achieved by the price controls.

decisions and enforcement of cap-and-trade programs with alternative permit banking and borrowing provisions. This work is motivated by programs that include permit banking provisions when regulators cannot rely on the perfect emissions monitoring provided by continuous emissions monitoring systems. The researchers constructed a dynamic programming model of compliance in emissions trading programs to examine the design of enforcement (levels of monitoring and violation penalties) when emissions permits are bankable and when emissions monitoring is imperfect. They focus on enforcement strategies that induce perfect compliance with minimal enforcement costs. This implies that no sanctioning costs are incurred; thus, minimizing enforcement costs requires minimizing monitoring effort[9].

The most important contribution of Stranlund *et al.* (2005) is to highlight the importance of enforcement strategies that motivate pollution sources to provide accurate self-reports of their emissions. They note first that the combination of imperfect emissions monitoring and bankable permits requires that firms self-report their emissions. The reason is that if a firm is not monitored in a particular period its emissions report is the only information available to a regulator to determine how many permits should be used for current compliance purposes and how many are carried into the future. Moreover, misreporting and the failure to hold sufficient permits must be classified as distinct violations. This is so because a firm that holds enough permits to cover its emissions during a given period may be motivated to under-report its emissions in order to increase the size of its permit bank[10]. That is, a firm

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[9] In the theoretical literature on compliance and enforcement in emissions trading, only Innes (2003) and Stranlund *et al.* (2005) allow for noncompliance in models with bankable permits. Innes argues that giving sources the ability to bank and borrow permits eliminates the need to impose costly sanctions to maintain compliance in these programs. He does not, however, examine the design of monitoring and punishment strategies that is the focus of Stranlund *et al.* (2005).

[10] Requiring self-reporting and making misreporting a distinct violation differs fundamentally from self-discovery and disclosure rules that seek to encourage greater compliance with environmental regulations by reducing penalties for violations that are voluntarily discovered and reported to authorities. For an example, see the U.S. EPA's Audit Policy (U.S. EPA 2000). Interestingly, most of the economic literature on self-reporting in

may comply with its permits but still be motivated to underreport its emissions.

Stranlund *et al.* (2005) demonstrate further that the high permit violation penalties (high relative to permit prices) that are characteristic of many emissions trading programs, including the SO_2 Allowance Trading Program and the EU ETS, have little deterrence value. The reason is that a strong incentive to bank permits and the common requirement to offset any permit violation with a reduction in a future permit allocation effectively eliminates the incentive to violate permits. In principle, permit violation penalties need to only cover the difference between the permit price for the period and the present value of the price in the next period, and hence, can normally be set very low. Moreover, setting a high permit violation penalty cannot reduce monitoring effort. In contrast, a penalty for under-reported emissions allows regulators to maintain compliance with imperfect monitoring, and setting this penalty as high as is practicable conserves monitoring costs. In short, the main challenge of enforcing cap-and-trade programs with permit banking is to motivate accurate and truthful self-reporting of emissions.

It is common in cap-and trade programs for the cap to become tighter as time goes by. This is true of the SO_2 Allowance Trading program and long-term proposals to cut greenhouse gas emissions like the American Clean Energy and Security Act of 2009 (U.S. Congress 2009). As the cap becomes tighter the nominal permit price will tend to increase. In fact, banking permits under conditions of certainty requires that the nominal price of permits should rise at the rate of discount (Rubin 1996, Schennach 2000). In turn, the incentive for sources to underreport their emissions increases over time. To counteract this either sanctions or monitoring intensity must increase. Since increasing monitoring is costly but increasing penalties typically is not, it is clear that to minimize the present value of monitoring costs over the life of the program it is the

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law enforcement assumes that self-reporting is a voluntary activity that can be encouraged by offering a lower penalty for self-reported violations (e.g., Malik 1993, Kaplow and Shavell 1994, Pfaff and Sanchirico 2000, and Innes 2001).

reporting violation sanctions that should respond as the permit price increases, not the level of monitoring. A simple way to do this it to make misreporting sanctions a constant multiple of realized permit prices. This keeps monitoring effort and compliance choices constant as permit prices increase. It has already been mentioned that tying sanctions to permit prices can shield compliance incentives and enforcement costs from price risk. An additional benefit of setting sanctions in this way is to stabilize compliance incentives and enforcement as nominal permit prices rise through time.

Like most environmental law, existing and proposed cap-and-trade programs rely heavily on self-monitoring and self-reporting of data used to determine compliance. This data includes not only emissions or estimated emissions and the data used for the estimates, but also quality assurance and quality control information related to the operation of monitoring technologies. While much attention has been given to the high permit violation penalties in the SO_2 Trading and other programs, these programs also make misreporting of emissions and other data separate violations from permit violations and they can feature heavy sanctions for false reporting. The U.S. Clean Air Act authorizes civil and criminal sanctions for false reporting under the SO_2 program. Each source must identify a single individual who bears the responsibility of submitting truthful reports, and who faces liability for misreporting (Tietenberg 2006, McAllister 2010). Sanctions for reporting violations in the EU ETS are left to member states. There is a lot of variation in these penalties, but they do include both financial sanctions and prison terms (European Environment Agency 2008)[11].

Like all matters concerning compliance in emissions trading programs, there are no empirical analyses using field data to test hypotheses concerning compliance behavior and enforcement strategies in dynamic trading environments. Two studies examine compliance and banking behavior

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[11] The member states of the EU ETS may require that third parties certify sources' emission reports before they are submitted to authorities (McAllister 2010).

in laboratory emissions markets[12]. Cason and Gangadharan (2006) motivated banking in their experiments by allowing subjects only imperfect control over their emissions. They found that permit banking reduced price variability associated with stochastic emissions, but that it also led to significant noncompliance and higher emissions. The latter result might be expected. The ability to bank permits activates additional demand for permits, which puts upward pressure on the permit price and the incentive not to comply. Thus, banking might have an indirect effect on noncompliance, because it induces higher permit prices. However, Cason and Gangadharan control for the price effect on compliance in their statistical analyses, so the banking effect they identify is a direct effect. This is a puzzle whose solution calls for additional research.

Perhaps because they were focused on how the ability to bank permits affected compliance choices, Cason and Gangadharan did not examine the distinct roles played by reporting and permit compliance in dynamic emissions markets. In contrast, Stranlund, Murphy and Spraggon (2011) designed their experiments specifically for this purpose. They motivated permit banking with a decrease in the aggregate supply of permits in the middle of multi-period trading sessions[13]. One of the authors' experimental treatments was parameterized to induce full compliance according to the model of Stranlund *et al.* (2005). This treatment featured imperfect monitoring, a modest reporting violation penalty, and a very low permit violation penalty. Both penalties were set below expected permit prices; the permit violation penalty was set at about one-quarter of the predicted price. Reporting and permit compliance rates in this treatment were quite high, about 96%

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[12] Muller and Mestelman (1998) review a number of other emission trading experiments that include banking provisions. None of them deal with the problem of noncompliance.

[13] The contraction in the permit supply at start of the second stage of the SO_2 Allowance Trading program was an important motivation for banking during the first stage of program (Ellerman and Montero 2007). Permit banking in laboratory experiments have been motivated by a variety of reasons. As noted, Cason and Gangadharan's (2005) experiments involved stochastic emissions. Subjects in Godby *et al.* (1997) were motivated by both stochastic emissions and a reduction in the permit supply. Cason *et al.* (1999) focused solely on banking motivated by a reduction in the permit supply.

and 92% compliance, respectively. This supports the hypothesis that high permit violation penalties have little deterrence value in emissions markets with bankable permits.

Stranlund *et al*. (2011) conducted a third treatment that reduced the monitoring probability by half to investigate the consequences of weak enforcement on dynamic emissions markets. As expected, there was significant noncompliance in this treatment, but nearly all of it involved reporting violations; permit compliance in this treatment remained high. This lends additional support for the notion that the main task of enforcement in dynamic emissions markets is to promote truthful self-reporting. Subjects in this treatment did not misreport as much as predicted, but this is not surprising since recall that we observe this phenomenon in other experimental and field settings. Moreover, despite weak enforcement and significant reporting violations, the permit market continued to function; in particular, subjects were able to allocate emissions through time reasonably well.

4. Lessons for cap-and-trade policies for greenhouse gas emissions

While the literature on the economics of enforcing cap-and-trade policies has progressed considerably, very little of it has focused on the control of markets for greenhouse gas emissions. In this section lessons from the previous sections are used to consider the compliance and enforcement consequences of several features of cap-and-trade-programs for greenhouse gas emissions.

4.1. Monitoring and sanctions

Perhaps the most difficult task in designing an effective cap-and-trade program for greenhouse gas emissions is obtaining accurate emissions data. This task may actually be more difficult for greenhouse gas control than for other programs. The first difficulty is the sheer number of sources. Recall that the EU ETS covers more than 11,000 sources of CO_2 emissions. A U.S. policy to control CO_2 emissions from large sources (10,000 metric tons or more annually) would involve 13,000 sources and cover just over half of U.S. greenhouse gas emissions (Pizer 2007)[14]. In addition, a comprehensive control policy would control emissions of several greenhouse gases. The American Clean Energy and Security

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[14] These are downstream sources, that is, sources that emit CO_2 directly into the atmosphere. An alternative is an upstream approach that would focus on the carbon content of fossil fuels at the point at which they are supplied to the economy (i.e., at the point of extraction, processing, distribution, or import). An upstream policy in the U.S. could cover nearly all CO2 emissions from fossil fuels by regulating only 3,000 sources (Pizer 2007).

Act of 2009 would have controlled emissions of CO_2, as well as methane, nitrous oxide, sulfur hexafluoride, perfluorocarbons, nitrogen trifluoride, and hydrofluorocarbons (U.S. Congress 2009). Emissions of these additional gases can be more difficult to monitor than CO_2 emissions (McAllister 2011).

Emissions monitoring in the EU ETS is likely to be a reasonable approximation of the way monitoring will be done in future cap-and-trade policies to mitigate climate change. While some sources may be required (or opt) to employ continuous emissions monitoring systems in future programs, most will rely on estimates of emissions based on activity data and emissions factors. Self-monitoring and self-reporting of these data will continue to be important elements of cap-and-trade enforcement. Moreover, it is almost certain that future trading programs will allow sources the limited ability to bank and borrow permits. Allowing intertemporal permit trading has proven to enhance the cost-effectiveness of emissions markets and to help contain uncertain abatement costs. I am not aware of any cap-and-trade policy to control greenhouse gas emissions (actual or proposed) that does not allow some form of permit banking and borrowing.

Under cap-and-trade policies with imperfect monitoring and intertemporal permit trading, both economic theory and laboratory experiments suggest that adopting strategies that motivate sources to provide accurate reports of their emissions, emissions estimates, and other data is the key to enforcement. High permit violation penalties have little deterrence value because of permit banking and the standard requirement that permit violations be offset with reductions in future permit allocations. Stringent requirements for self-monitoring and self-reporting along with stiff sanctions for reporting violations can conserve regulatory monitoring efforts, while high permit violation penalties cannot. Setting requirements and incentives to motivate accurate self-reporting should be the main task of enforcement strategies in trading programs to limit greenhouse gas emissions.

Some authors have suggested that permit violation penalties be used to provide safety valves to help control the uncertain abatement costs of greenhouse gas control. Using permit violation penalties in this way may require them to be set significantly higher than expected permit prices. However, in this article it has been noted that this is probably an inefficient way to provide permit price control for an emissions market. Instead of using the permit violation penalty as a safety valve, implementing an explicit price ceiling and floor for a trading program and enforcing the program to achieve full compliance can reduce expected enforcement costs and provide more efficient abatement cost control.

Finally, tying sanctions for reporting and permit violations to ongoing permit prices can be beneficial for two reasons. First, it allows sanctions to absorb variation in permit prices which can help shield monitoring effort and compliance outcomes from permit price volatility. Second, cap-and-trade programs for greenhouse gas emissions typically have declining caps over time, which implies that nominal permit prices and the incentive to underreport emissions increases over time. Tying sanctions for misreporting directly to prevailing permit prices shields monitoring effort and compliance choices from increasing permit prices.

4.2. Linking cap-and-trade programs

Analysts suggest that international efforts to control greenhouse gas emissions in the extended future will probably consist of perhaps many independent national and regional policies, rather than a comprehensive global system (Metcalf and Weisbach 2010). In fact, national and regional cap-and-trade policies have been proposed and implemented in several developed countries and inter-governmental bodies, including Australia, Canada, Japan and, of course, the European Union. In the absence of a federal U.S. policy to control greenhouse gas emissions, ten states in the northeast formed the Regional Greenhouse Gas Initiative. In addition, the California Air Resources Board proposed a cap-and-trade program to implement the state's Global Warming Solutions Act of 2006 (California Air Resources Board 2010). An important consideration, then, is whether and how to link independent cap-and-trade policies together. Although cap-and-trade policies can be linked together in several ways, linkage is usually taken to mean that sources under one program can trade permits with sources under other programs[15].

There are several potential benefits to linking cap-and-trade programs, but the most important is the potential to reduce overall abatement costs. If programs have different marginal abatement costs, then trading between the systems can lower the combined abatement costs of the systems in much the same way that trading permits among firms reduces aggregate abatement costs within a cap-and-trade program. Furthermore, linking trading programs can reduce price volatility, serving as another form of cost-containment measure, and limit concerns about market power and thin markets. Linking can also reduce leakage, which occurs when economic activity that causes the controlled pollution moves to another area with weaker control (Jaffe, Ranson and Stavins 2009).

There are also serious concerns about linking programs, some of which stem from the notion that the enforcement activities and compliance performance of separate programs are affected by each other when the programs are linked. To illustrate this issue, consider a simple model of two countries with domestic cap-and-trade policies for CO_2 emissions that are initially unlinked. Imagine in country A that enforcement is sufficient to induce full permit compliance by all covered sources, but that country B has a more difficult time enforcing its cap, such that it experiences significant noncompliance in its program. For simplicity, consider only permit violations and compliance. Assume further that expected marginal sanctions for permit violations are increasing in both countries and that penalty functions are not tied to permit prices. Finally total permit supplies in both countries remain constant after they link their programs together.

Suppose at first that the price of CO_2 permits is higher in country A than in country B. Differences in permit prices for unlinked systems can be generated by dif-

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[15] Discussions of the issues associated with linking cap-and-trade programs for greenhouse gas emissions can be found in Kruger *et al.* (2007), Jaffe *et al.* (2009), and Metcalf and Weisbach (2010).

ferences in permit supplies, aggregate marginal abatement costs, and enforcement effectiveness. In fact, CO_2 permit prices in country B could be lower, in part, because of weak enforcement. Now, if the countries link their programs together, sources in country A will purchase permits from sources in country B until the prices in the two countries are equalized, resulting in a decrease in the price of permits in country A and an increase in the price of permits in country B. The price change in country A produces greater emissions in this country, while its sources remain compliant. In fact, authorities might be able to reduce their enforcement effort in country A because of the lower price. In contrast, the increased price in country B implies that sources there will increase their violations, thereby putting greater pressure on enforcement efforts in that country to either keep violations in check or to sanction the greater number of violations. While violations in B increase, the increase in the permit price motivates sources there to reduce their CO_2 emissions. Unfortunately, this reduction in emissions is more than offset by the increase in emissions from country A, so aggregate emissions from the two countries increase as a result of linking[16].

Now suppose that the same conditions apply except that the price of permits is higher in country B than in A when the programs are not linked. Perhaps the high permit price is one reason that the authorities in country B find it difficult to maintain full compliance. Linking the programs together would result in country B sources purchasing permits from country A sources, increasing the permit price in A and reducing the permit price in B until they are equal. The increase in the price in country A would lead sources there to reduce their emissions, but could lead to noncompliance that did not exist before linking. On the other hand, the noncompliance incen-

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[16] To show this, let Q_A and Q_B be emissions from A and B, respectively, and let aggregate emissions be $Q_T = Q_A + Q_B$. Furthermore, let total permit holdings in A and B be L_A and L_B. These values are equal to the domestic permit supplies when the systems are not linked (i.e., the domestic caps), but they will be different from the domestic supplies when the systems are linked as permits flow between the two systems. Denote aggregate violations in A and B by $V_A = Q_A - L_A$ and $V_B = Q_B - L_B$. Finally, let Δ denote the change brought about by linking the programs. Then, because the aggregate supply of permits does not change and sources in country A continue to be fully compliant after linkage, it is straightforward to show that $\Delta Q_T = \Delta V_B > 0$.

tive in country B would be reduced even though sources there would increase their emissions. In the end, linking under these circumstances could lead to lower aggregate emissions[17].

The interconnection of enforcement and compliance performance continues after programs are linked. Anything that changes the demand for permits in one program will lead to changes in compliance incentives in other linked programs as their permit prices adjust. In fact, price risk can be transmitted across programs, an effect which has compliance and enforcement consequences. For example, suppose that the programs in countries A and B are linked, and for some unforeseen reason marginal abatement costs in country A are higher than expected. This will result in a higher permit price in both countries, increasing the noncompliance incentive and placing additional strain on enforcement resources in both countries.

The simple two-program model suggests several enforcement-related lessons for linking independent cap-and-trade programs together. Given fixed caps in the constituent programs of a proposed linked system, the process of linking will not have environmental consequences if all programs are enforced to achieve full compliance[18]. However, linking multiple programs can produce a change in aggregate emissions if some programs have compliance problems before or after linking. Moreover, linking can result in higher or lower aggregate emissions, depending on the distribution of permit prices and compliance outcomes in an unlinked setting, and how compliance outcomes react to changes in permit prices under the various programs.

Second, the price effects of linking programs can affect compliance incentives and the effectiveness

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[17] This would occur, for example, if linking did not lead to noncompliance in country A. If sources became noncompliant in A after linking, then the effect on aggregate emissions would depend on whether this increase in violations was larger than the decrease in the violations of sources in country B.

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

of enforcement strategies. Since linking programs together will tend to equalize permit prices across the programs, those that experience a permit price increase may also experience greater compliance and enforcement difficulties, while these difficulties may be reduced in programs that experience a decrease in the permit price. These price effects can continue after programs are linked as anything that affects permit demand in one program transmits price changes and their effects on compliance and enforcement across programs.

However, the price effects on compliance and enforcement of linking programs can be mitigated by tying sanctions directly to the going permit price. This suggestion has already been made for other reasons, one of which is that tying sanctions to permit prices can prevent price risk from being transmitted to compliance behavior and enforcement costs within cap-and trade programs. Sanctions set in this way absorb price changes so that compliance incentives and enforcement need not change. These kinds of sanctions are similarly beneficial in a multiple program setting because they can reduce or eliminate the price effects on compliance and enforcement that are transmitted across linked cap-and-trade programs.

4.3. Offsets

Many existing and proposed cap-and-trade policies allow sources to purchase abatement from sources not covered under a policy. These offsets can be of two types; credits may either be generated by reducing or by sequestering emissions (McAllister 2010). Examples of the first type include industrial facilities generating carbon offset credits by switching to lower carbon emitting fuels or by carrying out energy efficiency improvements. Moreover, coal mines, wastewater treatment plants, and landfill operations could generate credits by reducing methane emissions. Examples of projects to sequester carbon include the cultivation of new forests, managing forests to increase carbon storage, and the adoption of agricultural methods to store carbon in soils (Pew Center on Global Climate Change 2008)[19].

The main expected benefit of allowing offset credits in a cap-and-trade program is that the overall abatement costs of the program can be reduced if there is a significant supply of low-cost offsets available. For example, industrial sources under a cap-and-trade program may find it cheaper to invest in projects to limit deforestation or promote low-carbon energy sources in developing countries than to pursue additional reductions in their own carbon emissions. These opportunities can lower the aggregate marginal abatement costs of a cap-and-trade program, which would lower the price of emissions permits. Active offset markets may also yield additional benefits by producing incentives for technological advance beyond cap-and-trade programs, and by promoting the development of institutional capacity to control greenhouse gas emissions in other countries (Sigman and Chang 2011).

However, there are very serious monitoring and enforcement concerns associated with ensuring that offsets represent real emissions reductions. The number and variety of potential offsets makes monitoring their emissions reductions more complex than monitoring emissions (or more likely estimated emissions) from large point sources under the typical cap-and-trade program. Offset credits may come from a large number of smaller concerns, and measuring carbon sequestered in forests and soils may be more difficult than measuring greenhouse gas emissions leaving a large industrial source. Moreover, some projects must be monitored on a permanent basis, because the emissions reductions can be reversed in the future. For example, carbon sequestered in a

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[19] See Pew Center on Global Climate Change (2008) for examples of offset provisions in cap-and-trade proposals considered by the U.S. Congress. The Regional Greenhouse Gas Initiative and California's Global Warming Solutions Act of 2006 allow various kinds of offsets. 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 in developing countries that are parties to the Protocol. Offset credits are allowed in the EU ETS via the offset provisions in the Kyoto Protocol.

forest can be released if the forest is burned to clear the land for agriculture at a later date.

In addition, monitoring activities are not simply limited to the performance of an offset project. Regulators typically insist that offset projects be *additional*, meaning that the emissions reduction would not have occurred without the project. The requirement is meant to avoid purchasing offset credits from projects that would have been implemented anyway. Establishing the additionality of an offset project requires gathering information to establish a business-as-usual baseline. A related problem is that of *leakage*, whereby emissions reductions simply produce increased emissions elsewhere. For instance, a program to preserve forested land to sequester carbon may motivate increased timber harvests in another area. Thus, assessing the performance of an offset project may require additional monitoring to determine whether the controlled activity moved elsewhere.

Monitoring offset performance and sanctioning nonperformance is complicated by the fact that that the trade of offsets often involves different legal jurisdictions (Bushnell 2011). The regulatory authorities of a cap-and-trade program and those of another country that produces offsets must agree on and commit to procedures for monitoring the performance of offsets and levying sanctions in case the offsets do not produce the required emissions reductions. Additional monitoring and enforcement difficulties come from differences in the regulatory and legal capacities of regulators in the offset trade. Large supplies of offset credits from efforts to reduce emissions from deforestation and degradation (so-called REDD activities) are potentially available from developing countries. However, some of these countries lack the institutional capacity for environmental monitoring and enforcement, as well as the control of corruption, that would give their offsets credibility (Murray, Lubowski and Sohngen 2009; Deveny *et al.* 2009).

These enforcement challenges will likely lead to compliance problems in offset markets, as some credits are traded that do not represent actual emissions reductions[20]. This does not necessarily imply, however, that offset provisions in cap-and-trade programs are counterproductive in terms of controlling emissions or producing more efficient trading programs. In fact, Sigman and Chang (2011) show theoretically how offset provisions can produce higher abatement and lower emissions even if offsets involve higher enforcement costs and significant noncompliance. Their argument is straightforward. Suppose that enforcement of a particular cap-and-trade program is not sufficient to induce full compliance. Assume further that sanctions in this program do not vary with the permit price. Then, allowing purchases of offset credits outside the program will reduce the price of permits, which in turn will lead to reduced noncompliance[21]. Some portion of these offset credits may not be legitimate. However, violations and emissions will be lower if the reduction in violations by sources in the cap-and-trade program is larger than the violations in the offset market. In this case, the offset provision unambiguously enhances the efficiency of the cap-and-trade program despite higher enforcement costs and noncompliance in the offset market.

Efficiency can be improved even if offset provisions lead to higher emissions. Of course, if sources under a cap-and-trade program are fully compliant and they are allowed to purchase offset credits, some of which are illegitimate, then aggregate emission will increase. However, aggregate abatement costs in the program will be lower. Moreover, the lower permit price that comes from trading offsets could lead to a reduction in the costs of enforcing the cap-and-trade program, because of the reduced incentive to be noncompliant. The offset provision might enhance efficiency if the reduction in abatement and enforcement costs is greater than the costs of the legitimate offsets, their enforcement costs, and the environmental damage associated with higher aggregate emissions.

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[20] Wara and Victor (2008) offer a pessimistic view of the performance of the Kyoto Protocol's Clean Development Mechanism (CDM), saying that many CDM credits do not represent real emissions reductions, and that this poor performance is likely to get worse in the future.

[21] Similarly, Sigman (2011) argues that expanding markets to include sources that are more costly to monitor can increase compliance because the resulting lower permit price reduces the incentive not to comply.

The argument here is not that allowing offset credits always improves cap-and-trade programs. Enforcement and compliance problems associated with offsets could easily lead to worse environmental and economic outcomes. The main point is that these problems do not necessarily lead to bad outcomes. Careful estimates of the compliance and cost consequences of adding offset provisions to cap-and-trade programs are necessary to determine whether the provisions are worthwhile.

5. Conclusion

Policymakers, analysts, and various stakeholders now have a reasonably long history of experience with cap-and-trade pollution control programs. Moreover, these policies will continue to be a large part, if not dominate, proposals to control pollution into the foreseeable future. Experience and analysis have revealed much about the compliance and enforcement challenges that are unique to emissions markets. In particular, the economic literature has provided important insights into the nature of sources' compliance incentives and the effective and efficient design of enforcement strategies for cap-and-trade. The focus of this paper has been on highlighting these insights.

However, the enforcement challenges of emissions trading have perhaps become more difficult as cap-and-trade programs have been developed to control greenhouse gas emissions. These challenges include the monitoring and enforcement difficulties associated with controlling multiple pollutants from a wide variety of sources, international trade of greenhouse gas emissions among independent cap-and-trade-programs, and the management of offsets. While existing economic models and empirical tests can provide important lessons for the enforcement of these newer programs — and some of these lessons have been examined in this paper — they present unique challenges that have not received adequate attention in terms of rigorous theoretical analysis and empirical tests.

In all likelihood, the control of greenhouse gases will dominate environmental policy debates and the development of market-based solutions to pollution problems for many decades to come. Accordingly, the economics of enforcing cap-and-trade policies must continue to develop as new regulatory innovations emerge to confront climate change and other environmental problems.

References

Alm, J., & McKee, M. (1998). Extending the lessons of laboratory experiments on tax compliance to managerial and decision economics. *Managerial and Decision Economics*, *19*(4-5), 259-275.

Andreoni, J., Erard, B., & Feinstein, J. (1998). Tax compliance. *Journal of Economics Literature, 36*(2), 818-860.

Arguedas, C. (2008). To comply or not to comply? Pollution standard setting under costly monitoring and sanctioning. *Environmental and Resource Economics, 41*(2), 155-168.

Burtraw, D, Palmer, K., & Kahn, D. (2010). A symmetric safety valve. *Energy Policy, 38*(9), 4921–4932.

Bushnell, J. B. (2011). The economics of carbon offsets. In D. Fullerton & C. Wolfram (Eds.), *The design and implementation of U.S. climate polic*y. Chicago, IL,: University of Chicago Press, forthcoming.

California Air Resources Board (2010). California Air Resources Board gives green light to California's emissions trading program. Press release 10-63.

Cason, T. N., Elliott, S. R., & and van Boening, M. R. (1999). Speculation in experimental markets for emissions permits. In C. Holt & R. Mark Issac (Eds). *Research in experimental economics,* 7. Stamford. Conn: JAI Press.

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

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

Deveny, A., Nackoney, J., Purvis, N., Gusti, M., Kopp, R. J., Madeira, E. M., Stevenson, A. R., Kindermann, G., Macauley, M. K., & Obersteiner, M. (2009). Forest carbon index: The geography of forests in climate solutions. Resources for the Future.

European Commission (2003). Directive 2003/87/EC of the European Parliament and of the Council of 13 October 2003 establishing a scheme for greenhouse gas emission allowance trading within the

Community and amending Council Directive 96/61/EC. *Official Journal of the European Union*, L 275/32, 25.10.2003.

European Environment Agency (2008). *Application of the emissions trading directive by EU member States. Reporting Year 2008*. EEA Technical report No 13/2008.

Fell, H., & Morgenstern, R. (2010). Alternative approaches to cost containment in a cap-and-trade system. *Environmental and Resource Economics, 47*(2), 275-297.

Garvie, D., Keeler, A. (1994). Incomplete enforcement with endogenous regulatory choice. *Journal of Public Economics, 55*, 141-162.

Godby, R. W., Mestelman, S., Muller, R. A., & Welland, J. D. (1997). Emissions trading with shares and coupons when control over discharges is uncertain. *Journal of Environmental Economics and Management, 32*(3), 359-381.

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

Grull, G. and Taschini, L. (2011). Cap-and-trade properties under different hybrid scheme designs. *Journal of Environmental Economics and Management, 61*(1), 107-118.

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

Innes, R. (2001). Self enforcement of environmental law. In A. Heyes (Ed.). *The law & economics of the environment*. Cheltenham, England: Edward Elgar.

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

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

Jaffe, J., Ranson, M., & Stavins, R. N. (2009). Linking tradable permit systems: A key element of emerging international climate policy architecture. *Ecology Law Quarterly, 36*(4), 789-808.

Kaplow, L., & Shavell, S. (1994). Optimal law enforcement with self-reporting of behavior. *Journal of Political Economy, 103*(3), 583-606.

Kruger, J., Oates, W. E., & Pizer, W. A. (2007). Decentralization in the EU emissions trading scheme and lessons for global policy. *Review of Environmental Economics and Policy, 1*(1), 112-133.

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

Macho-Stadler, I.,& Perez-Castrillo, D. (2006). Optimal enforcement policy and firm's emissions and compliance with environmental taxes. *Journal of Environmental Economics and Management, 51*(1), 110-131.

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

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

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

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

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

Metcalf, G. E., & Weisbach, D. (2010). *Linking policies when tastes differ: global climate policy in a heterogeneous world* (Discussion Paper 2010-38). Harvard Project on International Climate Agreements, Belfer Center for Science and International Affairs, Harvard Kennedy School.

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

Montero, J., Sanchez, J. M., & Katz, R. (2002). A market-based environmental policy experiment in Chile. *Journal of Law and Economics, 45*(1), 267-287.

Montgomery, W. D. (1972). Markets in licenses and efficient pollution control programs. *Journal of Economic Theory, 5*(3), 395-418.

Muller, R. A., & Mestelman, S. (1998). What have we learned from emissions trading experiments? *Managerial and Decision Economics, 19*(4-5), 225-238.

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

Murphy, J. J., & Stranlund, J. K. (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.

Murray, B., Lubowski, R., & Sohngen, B. (2009). Including international forest carbon incentives in climate policy: Understanding the economics. Nicholas Institute for Environmental Policy Solutions, Report NI R 09-03.

Nordhaus, W. D. (2007). To tax or not to tax: alternative approaches to slowing global warming. *Review of Environmental Economics and Policy, 1*(1), 26-44.

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

Pew Center on Global Climate Change (2008). Congressional policy brief: Greenhouse gas offsets in a domestic cap-and-trade program. Available at http://www.pewclimate.org/docUploads/Offsets.pdf.

Pfaff, A. S., & Sanchirico, C. W. (2000). Environmental self-auditing: Setting the proper incentives for discovery and correction of environmental harm. *Journal of Law, Economics & Organization, 16* (1), 189-208.

Philibert, C. (2008). Price caps and price floors in climate policy: A quantitative assessment. International Energy Agency Information Paper. OECD/IEA.

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

Pizer, W. A. (2007). Scope and point of regulation for pricing policies to reduce fossil-fuel CO_2 emissions. Resources for the Future Issue Brief CPF-4.

Polinsky, A. M., & Shavell, S. (1992). Enforcement costs and the optimal magnitude and probability of fines. *Journal of Law and Economics, 35*(1), 133-148.

Raymond, L., & Cason, T. (2010). *An experimental study of affirmative and negative motivations for compliance in emissions trading programs* (Working Paper). Purdue University.

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

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

Schennach, S. (2000). The economics of pollution permit banking in the context of Title IV of the 1990 Clean Air Act Amendments.

Journal of Environmental Economics and Management, 40(3), 189-210.

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

Sigman, H. (2011). Monitoring and enforcement of climate policy. In D. Fullerton & C. Wolfram (Eds.), *The design and implementation of U. S. climate policy*. Chicago, IL: University of Chicago Press, forthcoming.

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

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

Stranlund, J. K., & Chavez, C. A. (2000). Effective enforcement of a transferable emissions permit system with a self-reporting requirement. *Journal of Regulatory Economics, 18*(2), 113-131.

Stranlund, J. K., Costello, C., & Chavez, C. A. (2005). Enforcing emissions trading when emissions permits are bankable. *Journal of Regulatory Economics, 28*(2), 181-204.

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

Stranlund, J. K., Murphy, J. J., & Spraggon, J. M. (2009). Imperfect enforcement of emissions trading and industry welfare: A laboratory investigation. In J. List & M. Price (Eds.), *Handbook on Experimental Economics and the Environment* (Forthcoming). Edward Elgar Publishing.

Stranlund, J. K., Murphy, J. J., & Spraggon, J. M. (2011). An experimental analysis of compliance in dynamic emissions markets. Forthcoming in *Journal of Environmental Economics and Management*.

Stranlund, J. K., & Joe Moffitt, L. (2011). *Enforcement and price controls in emissions trading* (Working Paper). Department of Resource Economics, University of Massachusetts-Amherst.

Tietenberg, T. H. (2006). *Emissions trading: Principles and practice* (2nd ed.). Washington, D. C.: Resources for the Future.

Torgler, B. (2002). Speaking to theorists and searching for facts: Tax morale and tax compliance in experiments. *Journal of Economic Surveys, 16*, 657-83.

U.S. Congress (2007). Low carbon economy act of 2007. S.1766, 110th Congress.

U.S. Congress (2009). American clean energy and security act of 2009. H.R. 2454, 111th Congress.

U.S. Environmental Protection Agency (2000). Incentive for self-policing, discovery, disclosure, correction and prevention of violations. *Federal Register*, *65*(70), 19618-19627.

U.S. Environmental Protection Agency (2003). *Section-by-Section Summary of the Clear Skies Act of 2003*. Washington, D. C.: U.S. EPA Office of Air and Radiation.

U.S. Environmental Protection Agency (2009). *NO_X Budget Trading Program: 2008 Highlights*. EPA-430-R-09-026. Washington, D. C.: U.S. EPA Office of Air and Radiation.

U.S. Environmental Protection Agency (2010). *Acid Rain and Related Programs 2009 Highlights: 15 Years of Results 1995 to 2009.* EPA-430-R-10-014. Washington, D. C.: U.S. EPA Acid Rain Program.

van Egteren, H., & Weber, M. (1996). Marketable permits, market power, and cheating. *Journal of Environmental Economics and Management, 30*, 161-173.

Wara, M. W., & Victor, D. G. (2008). *A realistic policy on international carbon offsets* (Working Paper 74). Stanford University Program on Energy and Sustainable Development.

Weber, T. A., & Neuhoff, K. (2010). Carbon markets and technological innovation. *Journal of Environmental Economics and Management 60*(2), 115-132.

Webster, M., Wing, I. S., & Jakobovits, L. (2010). Second-best instruments for near-term climate policy: Intensity targets vs. the safety valve. *Journal of Environmental Economics and Management, 59*(3), 250-259.

Weitzman, M. L. (1974). Prices vs. quantities. *Review of Economic Studies, 41*(4), 477-491.

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