Distributing Pollution Rights in Cap-and-Trade Programs: Are Outcomes Independent of Allocation?*

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Abstract

Standard economic theory predicts that if property rights to pollute are clearly established, the equilibrium outcome in an efficient emissions permit market will be independent of how the permits are initially distributed. This so-called independence property has very important implications for policy design and implementation. Empirical studies of existing emissions trading programs routinely find a strong positive correlation between the initial permit allocation and equilibrium emissions. This raises concerns that the independence property is failing to hold in real-world settings. Testing for a causal effect is difficult because of endogeneity and omitted variable bias. We exploit the random assignment of firms to different permit allocation cycles in Southern California's RECLAIM Program to test the independence of firms' initial permit allocations and emissions. Consistent with other programs, we find a very strong correlation between these two variables. However, when random assignment is used as an instrument for permit allocations, this statistical relationship disappears. We fail to reject the null hypothesis of no effect of the initial permit allocation on firm-level emissions.

JEL Classifications : D21, D23, H11, Q50, Q53, Q58

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1 Introduction

Market-based pollution permit trading programs have moved to the front and center of industrial environmental regulation. A particularly appealing quality of the "cap-and-trade" (CAT) approach to regulating industrial emissions is that an efficient permit market will direct firms with the lowest abatement costs to reduce emissions first (Coase, 1960; Dales, 1968; Montgomery, 1972). Importantly, provided a series of conditions are met, this efficient allocation of abatement activities will be achieved regardless of how the emissions permits are initially allocated.[1] This paper presents empirical evidence on the relationship between the initial allocation of permits and the ultimate distribution of permitted emissions in a landmark cap-and-trade program.

The independence of permit market outcomes and the initial allocation of permits helps to explain why cap-and-trade systems have emerged as the preferred instrument in a variety of environmental policy settings (Hahn and Stavins, 2010). If the initial distribution of permits plays no role in determining emissions and abatement outcomes in equilibrium, emissions permits can be freely allocated to pursue political objectives (such as establishing a constituency for the market-based regulation) without compromising the economic efficiency of permit market outcomes.[3]

The theory literature has identified several conditions under which the so-called independence property might fail to hold.[4] For example, Hahn (1984) shows that the final allocation of permitted emissions can depend upon the initial distribution of permits if permit markets are imperfectly competitive. Stavins (1995) demonstrates that the permit market equilibrium can be sensitive to the initial allocation of permits in the presence of transaction costs. Montero (1997) shows that

[1] Conditions include zero transaction costs, full information, perfectly competitive markets, and cost minimization behavior.

[3] Several economists have explored how permit allocation can be used to enhance the political feasibility of emissions trading programs. See, for example, Bovenberg and Goulder (2001), Bovenberg et al. (2005), Dinan and Rogers (2002).

[4] For an excellent and comprehensive review of the conditions under which the independence property may – in principle –break down, see Hahn and Stavins(2010).

when firms face transaction costs in the permit market and are uncertain about whether their permit trades will be approved, firm-level emissions are more likely to be increasing with initial permit allocations. Fowlie et al. (2012) note that the independence property may fail to hold in a dynamic setting where firms' entry and exit decisions are contingent upon how permits are allocated.

These concerns notwithstanding, free allocation of emissions permits as compensation for industrial stakeholders has played a critical role in securing political support for CAT programs (Joskow and Schmalensee, 1998; Hahn and Stavins, 2010). This practice has been predicated on the notion that the independence property will hold in applied policy settings. Notably, the Courts have begun to question this independence, noting that "the market would only bear out that assumption if the transaction costs of trading emissions were small, which is hardly likely." (North Carolina v. EPA, No. 05-1244 (D.C. Cir. Jul. 11, 2008)).[5] In fact, real-world policy settings are complicated by a host of market imperfections and related distortions. If these imperfections are resulting in substantive violations of independence property, this has important implications for policy design and implementation.

A growing empirical literature seeks to shed light on this issue. One potentially meaningful finding, documented across range of cap-and-trade-programs, is that a significant share of the allowances retired each year for compliance purposes are surrendered by the same firms to which they were initially allocated (Ellerman, 2004; Gangadharan, 2000; Hanemann, 2009; Kerr and Mare, 2008; Montero et al. 2002).[6] One measure of this phenomenon, referred to as autarkic compliance

[5]The U.S. Court of Appeals for the D.C. Circuit ruled unanimously against the Clean Air Interstate Rule which was intended to be the largest, most comprehensive CAT program in U.S. history. IIn this ruling, the court openly questioned the assumption that equilibrium emissions would be independent of the initial allocation.

[6]In the much heralded Acid Rain Program, it is estimated that less than 30 percent of the allowances retired each year for compliance purposes were surrendered by a source other than the source to which the permit had been allocated (Kreutzer, 2006). A similar degree of autarkic compliance is found in the US lead trading program (Kerr and Mare, 2008). Montero (2002) finds very limited trading activity in an emissions trading program in Santiago, Chile. Gangadharan (2000) finds striking rates of non-participation in Southern California's RECLAIM

in the literature, is a strong positive correlation between the initial permit allocation and the equilibrium distribution of permitted emissions (Hanemann, 2010; Kreutzer, 2006). Researchers offer a variety of explanations for this autarkic behavior, including transaction costs (Gangadharan, 2000), managerial preferences for keeping emissions within the allocated limit (Malloy, 2002; Sandoff and Schaad, 2006), regulatory uncertainty (Montero et al., 2002), the endowment effect (Murphy and Stranlund, 2005), and loss aversion (Kreutzer, 2006).[7] Whatever the explanation, low levels of trading activity in emissions trading programs is sometimes interpreted as evidence that permit markets are failing to fully exploit gains from trade, and that the initial permit allocation may be playing a role in determining permit market outcomes (Hanemann, 2009).

In this paper, we carefully consider the relationship between the initial permit allocation and the equilibrium distribution of permitted emissions. Our starting point is that a strong positive correlation between permit allocations and emissions is consistent with, but not proof of, a violation of the independence property. Formally testing for a causal relationship between permit allocations and emissions is complicated. Researchers typically observe the initial permit allocation and the operating choices of firms subject to cap-and-trade regulation over time. If emissions permits were randomly allocated to firms in the same emissions trading program, identifying an effect of the initial permit allocation on emissions would not be so difficult. However, firms' initial permit allocations are typically determined by historic emissions and/or ex ante expected abatement costs, both of which likely affect firms' emissions. This endogeneity of emissions seriously confounds our ability to credibly identify the effect of permit allocations on emissions.

This paper uses detailed data from Southern California's Regional Clean Air Incentives Mar-

trading program. More recent studies of the EU ETS show firms expressing a preference for autarkic compliance strategies (Pinske, 2008; Sandoff and Schaad, 2009). Finally, evolving markets for water pollution across the United States have so far generated minimal trades ("Environmental Markets at Centre of Chesapeake Clean-Up Plan", Environmental Finance, May 2010).

[7] Hanemann(2010) provides an excellent review of the literature that seeks to explain firms' apparent preference for autarky in emissions trading programs.

ket (RECLAIM) to test for a causal relationship between firms' initial permit allocations and emissions. The RECLAIM market was the first emissions trading program to incorporate a broad range of industries and sectors. It has the longest history of any locally designed and implemented CAT program. Transaction costs and regulatory uncertainty are well documented in the RECLAIM market (Gangadharan, 2000; Schubert and Zerlauth, 2000; US EPA, 2002). Consequently, we might expect to find a relationship between firm-level emissions and the initial permit allocation in this particular market context.

The RECLAIM program is particularly well suited for a study of the relationship between firm level allocations and emissions. First, firm-level permit allocations (completely determined at the outset of the RECLAIM program) vary both across firms and across time. Significant *within-firm* variation in permit allocations facilitates the inclusion of firm-level fixed effects in our estimating equation, thus purging our estimates of all permanent plant characteristics that determine both emissions and initial permit allocations.

While firm-level fixed effects remove the influence of long-run determinants of both permit allocations and emissions, they are not a panacea for omitted variables bias. Over the time period we study, not only were firm-level permit allocations decreasing at firm-specific rates, but the aggregate emissions cap became increasingly more stringent. Our fixed-effects estimates will be biased if the firm-specific, cost-minimizing responses to the tightening of the aggregate emissions cap are correlated with the firm-specific parameters that defined the permit allocation trajectories. In fact, because permits were disproportionately allocated to sources where compliance costs were expected to be relatively high, this kind of correlation seems quite plausible. To address this endogeneity problem, we exploit a very unusual design feature of the RECLAIM program which randomly assigns firms to permit allocation cycles. We use this random assignment as an instrument for firm-level permit allocations.[8]

The main empirical findings are as follows. First, consistent with past findings, we document a strong positive relationship between firm-level emissions and permit allocations in the cross-section. If this statistical relationship were to be interpreted as causal, we would conclude that a 1 percent increase in the number of permits allocated to a firm increases emissions by 0.8 percent. When we include firm-level fixed effects, the strength of the relationship attenuates, but the relationship remains strong, economically significant, and positive. When we instrument for firm-level permit allocations using only the variation generated by random assignment to compliance cycles, the relationship between firms' permit allocations and emissions disappears. We fail to reject the hypothesis that firm-level emissions in equilibrium are independent of how RECLAIM permits were initially allocated. These results should be interpreted with some care. Although our OLS estimates are rejected, we cannot confidently rule out all economically significant positive effects of permit allocations on emissions. We conclude that our empirical results are consistent with - but not proof of- the independence property.

Section 2 introduces the identification problem that complicates the interpretation of a strong positive correlation between permit allocations and emissions. Section 3 provides an overview of the RECLAIM program. Section 4 describes the data and provides some summary statistics. Section 5 presents the empirical results. Section 6 concludes.

2 The Econometric Identification Problem

We adopt a simple factor demand approach to modeling a firm's emissions choices in the short run. We first use the model to highlight the factors that, in theory, determine a firm's choice of

[8]This identification strategy is similar in spirit to Ellerman and Reguant (2008) who exploit the fact that Spanish coal-fired electricity generating units were allocated emissions allowances using a function that rewards certain cleaner sources. These authors find no systematic relationship between the initial endowment and production decisions at the unit level

emissions. In subsection B, we use the model to demonstrate some conditions under which a firm's permit allocation affects the emissions choice. Subsection C discusses the econometric challenges inherent in estimating this relationship.

A Derived Demand for Emissions

We assume that profit maximizing firms operating in perfectly competitive input and output markets produce output q using inputs $\mathbf{x} = [x_1, ...x_k]$. We further assume that production technologies can be represented by strictly concave, twice differentiable production function $q(e, \mathbf{x}; z)$, where e denotes emissions (modeled as an input to production), $\mathbf{x}$ is a vector of other inputs, and z denotes the the fixed operating characteristics that define the production technology or process. For expository purposes, we consider the simple case of a production process that employs two variable inputs: emissions e and a generic input x. We rule out corner solutions.

Firms' emissions are regulated under a CAT program in which emissions permits are distributed *a gratis* at the outset of the program. A firm's initial permit allocation is denoted by A. We assume that this initial allocation is completely determined at the outset of the program; the number of permits the firm receives from the regulator does not depend on the firm's future choices of inputs or output levels. To remain in compliance, firms must hold permits to offset any uncontrolled emissions. Firms act as price takers in the permit market; the permit price is τ.

The indirect profit function for a representative firm is given by:

$$\pi = Pq(e, x; z) - \omega_x x + \tau(A - e).$$

This profit function is assumed to have the usual properties: π is increasing in the product price P and non-increasing in input prices w.

By Hotelling's lemma, input supply and factor demand functions are implicitly defined by the first order conditions for profit maximization:

$$P\frac{\partial q}{\partial e} = \tau$$
$$P\frac{\partial q}{\partial x} = \omega_x$$

After totally differentiating this system with respect to emissions and the exogenous variables, we can use Cramer's rule to identify the signs of the partial derivatives of the emissions function:

$$\frac{\partial e}{\partial \tau} = \frac{Pq_{xx}}{|H|} < 0 \tag{1a}$$
$$\frac{\partial e}{\partial P} = \frac{Pq_{ex}q_x - Pq_{xx}q_e}{|H|} \tag{1b}$$
$$\frac{\partial e}{\partial w_x} = \frac{-Pq_{ex}}{|H|} \tag{1c}$$
$$\frac{\partial e}{\partial A} = 0 \tag{1d}$$

Intuitively, equation (1a) implies that a firm's profit maximizing choice of emissions is decreasing in τ.[9] By equation (1b) emissions are most likely to be increasing in P.[10] The response of firm-level emissions to changes in w_x will depend on whether x and e are substitutes or complements.

In this simple model, the firm's choice of emissions is completely independent of its initial permit allocation A. However, previous work has identified conditions under which this independence might fail to hold. For instance, consider the implications of introducing transaction costs

[9] The second order conditions for profit maximization imply that $|H| > 0$. By assumption, $q_{ee}(e, x; z) < 0$ and $q_{xx}(e, x; z) < 0$.

[10] The firm will increase its emissions in response to an increase in the product price P if $q_{ex}q_z > q_{xx}q_e$. Although we cannot conclude that the firm will always increase emissions when the price it receives for its product increases, the circumstances under which q_{ex} will be sufficiently negative such that the firm reduces emissions when the product price increases are unlikely for most common production functions.

into the model. Let u denote the quantity of permits traded by the firm: $u = (e - A)$. Following Stavins (1995), we define a common transaction cost function, $T(u)$, for which $T'(u) > 0$ and for which $T''(u)$ can be positive, negative, or zero valued.

The firm's profit function can now be written:

$$\pi = Pq(e, x; z) - \omega_x x + \tau A - \tau e - T(u).$$

Equations (1a), (1b), and (1c) are unaffected by the introduction of these transaction costs. However, the partial derivative in (1d) becomes:

$$\frac{\partial e}{\partial A} = \frac{T_{eA} P q_{xx}}{|H|}.$$

If marginal transaction costs are increasing (decreasing) with u, firm-level emissions will be negatively (positively) correlated with permit allocations.

More generally, if the costs of obtaining (or selling) emissions permits, $C(u)$, varies non-linearly with u, the independence property fails to hold. The literature points to several reasons why we might observe non-linearities in $C(u)$. For example, Montero (1998) considers regulatory uncertainty regarding whether the transaction will be approved. The likelihood of approval varies non-linearly with u. This form of uncertainty increases the likelihood that firms' initial permit allocations will positively affect their profit maximizing choice of e.

Finally, it has been noted by Malloy (2003) and others that this kind of modeling approach (i.e. one that assumes the firm simply pursues profit maximization, converting inputs into outputs in response to market signals), ignores important and nuanced dimensions of firm decision-making. Viewing the firm as an organization with a multiplicity of actors, management styles and objective functions opens up additional explanations for why a firm's choice of emissions might be influenced by its initial permit allocation (Hanemann, 2010; Von Malmborg, 2008).

B Econometric challenges

Thus far, we have identified some important determinants of a firm's emissions demand including input prices, the permit price, the price the firm receives for its products, and technology operating characteristics. The initial permit allocation can also play a role in determining firm-level emissions if, for example, transaction costs are a non-linear function of u or if firms have a managerial preference for an autarkic compliance strategy. We are interested in empirically testing whether the number of permits initially allocated to a firm affects the firms' demand for emissions inputs.

The following econometric model that serves as the basis for our empirical tests:

$$\begin{aligned} e_{it} &= \phi A_{it} + \beta' X_{it} + \boldsymbol{\delta}_t + \eta_{it}, \qquad (2) \\ \eta_{it} &= \alpha_i + \varepsilon_{it}. \end{aligned}$$

The dependent variable, e_{it}, is the log of emissions at firm i in time t; A_{it} is the log of the firm's permit allocation in time t. The δ_t's denote a full set of time effects that capture common shocks to (common trends in) the emissions across all firms in the program. X_{it} is a vector of input prices and producer prices that vary both across firms and time. The error term η_{it} captures the effects of any omitted variables. This error term can be decomposed into omitted, permanent, firm-specific omitted factors, α_i, and a residual ε_{it}. The coefficient ϕ captures the effect of the initial permit allocation on firm-level emissions. If firm-level permit allocations A_{it} are correlated with the error in equation (2) then ϕ will not be consistently estimated by Ordinary Least Squares (OLS).

Consistent estimation of ϕ is complicated by the manner in which permits are typically allocated to firms in cap-and-trade programs. It is standard for policy makers to allocate relatively more emissions permits to those firms that have historically accounted for a larger share of emissions or anticipate disproportionately high emissions abatement costs. In other words, A_{it} is determined by a set of factors that are expected to significantly determine the firm's emissions under the emissions trading program. If we do not adequately control for these factors, the A_{it} will be correlated with the η_{it}.

If firm-level permit allocations vary significantly over time, we can use within firm variation to identify an effect of permit allocations on firm-level emissions. This purges our estimates of the effects of time-invariant factors that determine both permit allocations and emissions. However, this strategy does nothing to control for time-varying omitted factors which can be particularly problematic in this setting. As firm-level permit allocations decrease over time, so too does the aggregate emissions cap. In an efficient permit market characterized by abatement cost heterogeneity, we should expect heterogeneous emissions responses across firms to the tightening of the aggregate cap. For example, a cost minimizing firm with relatively low abatement costs will respond by reducing its emissions substantively over time, whereas a firm with relatively high abatement costs will reduce emissions less, if at all. If these cost-effective, firm-specific responses to changing permit market conditions are correlated with the rate at which firm-specific permit allocations decrease over time, the fixed-effects estimator of ϕ will be biased.

One solution to this identification problem would involve allocating emissions permits (and the rate at which permit allocations decrease over time) randomly across firms. This would assure that the variation we are using to estimate the ϕ parameter is independent of other factors that determine emissions. Although an ideal research design, random allocation of permits across stakeholders is unlikely to be politically viable or desirable in any meaningful policy context. In the absence of purely experimental data, we exploit an unusual design feature of Southern California's

RECLAIM program which generates exogenous variation in the timing of firms' permit allocations. In the sections that follow, we describe this emissions trading program and demonstrate how it provides a unique opportunity to empirically investigate the relationship between initial permit allocations and emissions.

3 Background: The Regional Clean Air Incentives Market

The South Coast Air Quality Management District (SCAQMD) covers a 10,740 square mile area of southern California including all of Orange county and parts of Los Angeles, Riverside, and San Bernadino counties. Ozone concentrations in the this district exceeded state standards on 184 days in 1991 (Hall, 1996).[11] To confront these and other air quality issues, the SCAQMD began to consider market-based regulatory alternatives in the early 1990s. Regulators introduced the RECLAIM program in 1994 to bring the region into compliance with state and federal air quality emissions standards at minimum cost. A majority of the firms in the SCAQMD emitting four tons per year or more of nitrogen oxide (NOx) were included in the NOx trading program.[12]

At the outset of the program, RECLAIM included 392 sources owned and operated by both the private sector and government agencies (Prager et al., 1996; Schubert and Zerlauth, 1999). Of these, 72 percent were manufacturing firms; 13 percent in communication, transportation or utilities; 2 percent were construction operations; 3 percent were in the service sector; 6 percent in wholesale; 2 percent were in retail; and the remaining 2 percent were government entities.

The RECLAIM program imposed a mandatory cap on the total quantity of permitted NOx emitted by sources in the program. The cap was primarily designed to meet emissions reductions

[11] Adverse effects of ozone exposure include damage to lung tissue, aggravation of asthma and other respiratory problems, a reduction in the ability of plants to produce and store food, fish kills, and reduced visibility.

[12] Certain sources are categorically excluded from RECLAIM, including restaurants, police and fire fighting facilities, potable water delivery operations, and all facilities located in the Riverside County and Los Angeles County portions of the Southeast Desert Air Basin.

targets for the years 2000 and 2003. A corresponding number of Reclaim Trading Credits (RTCs) were allocated to RECLAIM sources at no cost. An RTC confers the right to emit one pound of NOx emissions and is valid for one year. Firm-specific allocation schedules, which specified how many permits each firm receives over the duration of the program, were determined and made public in 1994. Section B provides a detailed description of how SCAQMD allocated permits to firms in RECLAIM.

A Complying with the RECLAIM program

To remain in compliance with the RECLAIM program, a firm has several options including reducing production, increasing operating efficiency, installing abatement technology, or purchasing permits.[13] If a firm reduces its emissions below its permit allocation, it can sell excess permits in the market to other firms.[14] Studies and surveys of market participants indicate that, in the first ten years of the program, most firms achieved compliance through short run changes in production processes such as fuel substitution, versus major capital investments in abatement equipment (SCAQMD, 2000; Schubert and Zerlauth, 1999; US EPA, 2006).

Emissions are reported and compliance is certified quarterly. A compliance "cycle" lasts twelve months. At the conclusion of each of the first three quarters of the cycle, firms have 30 days to acquire any RTCs necessary to reconcile their permit holdings with their emissions. Firms are subject to penalties for quarterly shortfalls.[15] Firms have 60 calendar days following the last day of each compliance cycle to reconcile fourth quarter emissions with their permit allocation

[13] Initially, RECLAIM facilities also had the option to offset emissions by purchasing and scrapping pre-1982 vehicles. This option was later revoked. Over the course of the program, 10 firms used these "mobile source credits" to offset emissions.

[14] By 2003, 12% of RECLAIM facilities had not participated in the market, 13% had participated as buyers only, 19% as sellers only, and 55% had acted as both buyers and sellers.

[15] Facilities that fail to hold sufficient RTCs are required to surrender permits in future periods to cover the shortfall and can be subject to large civil financial penalties.

and purchases (SCAQMD, 1993b; US EPA, 2006).[16] Transfers of allowances between compliance periods is not permitted because regulators wanted to guard against temporal concentrations of NOx emissions. A permit can only be used to offset emissions during the compliance period it is allocated.

SCAQMD estimates that the average compliance rate (i.e. the percentage of firms that complied with rules of the program) was approximately 90% from 1994 through 1997 (US EPA, 2002). A 1998 SCAQMD document suggests that non-compliance prior to 1998 was likely due to misunderstanding of the regulation or mistakes in calculation (Lieu, 1998). Evidence of non-compliance is particularly strong in 2000 when electricity generators could make unusually high profits in California's wholesale electricity markets that substantially exceeded the fines associated with exceeding emission allowances(Kolstad and Wolak, 2008). After 2001, compliance has approached 100 percent.

B Allocating emissions permits in RECLAIM

Policy makers recognized the significance of permit allocations and clearly established firm-specific allocation schedules prior to formal adoption of the program (SCAQMD, 2007). Firm-specific permit allocation schedules specified exactly how many RTCs the firm would receive (for free from the implementing agency) each period. Over the first ten years of the program, firm-specific allocation schedules ratchet down every twelve months.

The allocation methodology, including the formulas, the production bases and device-specific emission factors used to determine each firm's permit allocation schedule, are clearly laid out in

[16] SCAQMD rule 2004 states that the reconciliation period following the end of a quarter shall be used to reconcile allocations only with emissions from that quarter. A lawsuit filed in September 2003 alleged that SCAQMD has, in some instances, failed to conduct quarterly audits. The case settled in favor of the plaintiffs (Communities for a Better Environment and Our Children's Earth Foundation vs. SCAQMD et al., Case No. 03-06985 WMB (CTx)).

SCAQMD Rule 2002: *Allocations for Oxides of Nitrogen (NOx) and Oxides of Sulfur (SOx).* Two key parameters define the downward trajectory of a firm's permit allocations over the first ten years of the RECLAIM program:

$$\begin{aligned} P1_i &= \sum_d B_{di} \cdot f1_d + ERC_i \\ P2_i &= \sum_d B_{di} \cdot f2_d + ERC_i. \end{aligned} \tag{3}$$

The first parameter, $P1_i$, defines the number of permits allocated to firm i in the first compliance cycle. The second parameter, $P2_i$ determines the firm's RTC allocation in the seventh compliance cycle beginning in 2000. Over the period 2000-2003, all allocation trajectories decrease at a common rate. In aggregate, the required reductions in 2000 and 2003 were based on the emissions reductions specified by SCAQMD's 1991 Air Quality Management Plan (AQMP).

For each NOx source or process unit at firm i (indexed by d), historical throughput B_{di} was multiplied by a device or process specific emissions factor f_d. The throughput measures were defined to be the maximum annual throughput at the firm between the years 1989 to 1992.[17] SCAQMD justified the use of maximum (versus average) historical throughput on the grounds that the baseline period was a time of economic recession (Schwarze and Zapfel, 2000).

For all devices and production processes covered by the RECLAIM program, Rule 2002 specified equipment-specific starting factors ($f1$) and ending factors ($f2$). These factors were based upon a review of technologically viable control methods that took into account the emissions, energy, and economic impacts for all known NOx emissions reduction technologies in each source category. Greater (smaller) reductions were required of processes and technologies associated with

[17] These measures where based on annual emissions reports whenever possible. For those facilities that had not submitted emissions reports during 1989-1992 period, device-specific throughput measures were based on information about facility operations and device characteristics.

relatively low (high) cost emissions abatement options. To determine the applicable emissions factors, equipment at each firm was categorized based on permitting information about the production process, equipment size, heating capacity, etc. Finally, firm-specific allocation trajectories were adjusted to reflect the number of certified emissions reductions (ERCs) held prior to 1994.

New firms entering the program after 1994 are required to obtain sufficient RTCs to offset their NOx emissions.[18] These RTCs must be obtained through the trading market and are not issued to the firm. When an incumbent firms close, the firm retains its RTC holdings. These can be held as an investment or transferred to another firm.

Before the RECLAIM program got underway, regulators were concerned that firms might not plan sufficiently for their fourth quarter emissions. Because permits are only valid for use in the compliance cycle to which they are allocated, regulators feared that a failure to set aside sufficient permits to cover the fourth quarter emissions would create unnecessary price volatility and result in insufficiency liquidity in the permit market (Carlson et al. 1993). To avoid this problem, regulators chose to randomly assign firms to one of two staggered twelve month compliance cycles. Placement in either cycle was determined by computer-generated random assignment (SCAQMD, 1997). RTCs allocated to Cycle 1 firms are valid from January 1 through December 31. RTCs allocated to Cycle 2 firms, in contrast, are valid from July 1 through June 30. A firm can comply using valid permits of either cycle.[19]

[18] A small reserve of RTCs was set aside for new, low emitting new entrants.

[19] Ellerman, Joskow, and Harrison (2003) note that these overlapping cycles increase, to a limited extent, intertemporal flexibility in when permits can be used for compliance.

C Transaction costs

The theoretical literature suggests that a firm's emissions might not be independent of its permit allocation if participating in the permit market incurs transaction costs.[20] Firms participating in RECLAIM can incur both explicit and implicit transaction costs. Prior to entering the RTC market, a firm must learn how the program works and determine what it would cost to reduce emissions internally. If a firm decides that it wants to participate in the RTC market, it must find a trading partner, negotiate a transaction and hire any legal, insurance, and brokerage services it deems necessary. firms also incur a transaction fee, split equally between the buyer and seller, that helps to fund the administration of the RECLAIM program.[21]

When the RECLAIM program was introduced, no institutional arrangements were made to facilitate trading. Initially, firms wishing to trade RTCs had to find their own trading partners. However, shortly after the program was introduced, an electronic auction program was developed by Ace Markets Inc. and various firms began offering brokerage services. The fraction of RTC transactions involving private-sector brokers increased from 38 percent in 1994 to 75 percent by 2001.

Several surveys of RECLAIM market participants have collected information about transaction costs. Early on, brokers reported charging a fixed fee of $150 per trade and a variable fee of 3.5 percent of the transaction value (Burnside et al., 1996). In a more recent survey, market participants estimated that total broker fees amounted to 1 percent to 3 percent of the total value of the trades (US EPA, 2002). RECLAIM firms also report having to devote considerable human

[20]Stavins (1995) and Montero (1997) investigate how, in theory, the post-trading equilibrium can be sensitive to how permits are initially allocated (for free) to facilities. Stavins develops a theoretical model of a cost minimizing firm whose emissions of a uniformly mixed flow pollutant are subject to cap-and-trade regulation. Transaction costs are assumed to be a function of the number of permits sold. He concludes that, if marginal transaction costs are increasing (decreasing), firm-level emissions are increasing (decreasing) with firm-level permit allocations. Montero (1997) later demonstrates how, in the presence of uncertainty or transaction costs, the permit market equilibrium can be sensitive to the allocation of permits, even when marginal transaction costs are constant.

[21]As of 2006, this fee was $100.75 per transaction (US EPA, 2006).

resources to learning about the RECLAIM market and monitoring compliance status (Schubert and Zerlauth, 2000).

In summary, relatively insignificant, explicit transaction costs and potentially large, implicit transaction costs are well documented in RECLAIM. Gangadharan (2000) provides evidence to suggest these explicit and implicit costs have discouraged participation in the early years of the RECLAIM market.

D Regulatory uncertainty

In markets where both transactions costs and regulatory uncertainty are present, we might be more likely to find a positive relationship between firm-level emissions and permit allocations (Montero, 1997; Ben-David et al., 2000). In evaluations of the RECLAIM program, regulatory uncertainty has been identified as a key issue that has allegedly undermined the success of RECLAIM(US EPA, 2006). Here, we briefly discuss two sources of uncertainty surrounding compliance and enforcement.

First, questionable brokerage practices in RECLAIM have created considerable uncertainty about compliance approval. One of the major RTC brokers, the Automated Credit Exchange, has been sued repeatedly for failing to deliver RTCs that were paid for by their clients.[22] Furthermore, 17 substantive amendments to the RECLAIM program rules since 1994 have exacerbated uncertainty about how the regulation will be interpreted and enforced (EPA, 2006).[23]

Emissions monitoring and enforcement practises have also created considerable uncertainty about compliance approval. If emissions data for a RECLAIM source are missing, the regulator

[22] Jacob, Chip. "Smoke and mirrors." *Pasadena Weekly.* Thursday Dec. 12, 2002. 14-18.

[23] For example, following the electricity crisis of 1999-2000, the structure of the program was fundamentally changed when electricity generators were removed entirely from the RTC market.

computes the source-specific maximum possible emissions for the period over which reports are missing. If the regulator concludes ex post that a firm did not have sufficient permits to cover its reported or imputed emissions, the firm's subsequent allocation is reduced by the total amount of the violation. Non-compliance can also be punished by stiff monetary penalties, although the penalties are not automatic and are negotiated on a case by case basis (Stranlund, 2000).

4 Data and descriptive statistics

To construct the data set used in this analysis, we submitted multiple public records requests to the agency that oversees the RECLAIM program. We have obtained firm-level information regarding industrial operations, compliance cycle assignment, variables used to determine initial RTC allocation schedules, annual RTC allocations, and quarterly emissions certifications. Appendix 1 includes a more detailed description of the data.

This section has three subsections. Subsection A documents trends in both emissions and permit allocations over the duration of our study. In subsection B, we demonstrate a high level of consistency between the permit allocations we observe in the data and the permit allocation rules and protocols as defined by the implementing agency. Subsection C characterizes the variation that is generated by random cycle assignment.

A Emissions and permit allocations

SCAQMD maintains a detailed database tracking all NOx permits and firm-level emissions in RECLAIM. From these data, we recovered the NOx permit allocation schedules for the RECLAIM firms that comprised the program "universe" when the program was being designed and implemented. Some of the firms in this initial universe were ultimately excluded from the RECLAIM program either because they shut down operations or because information certified after the initial audit demonstrated that their baseline emissions fell below the threshold for participation.[24] We exclude these firms from our analysis. In total, 377 of the firms in the original universe reported and certified emissions during our study period.

Figure 1 plots NOx emissions and RTC allocations over the period 1994-2004. To generate this figure, annual RTC allocations are divided equally across the four quarters of the corresponding compliance cycle. The aggregate emissions cap, or the total quantity of permits allocated to firms in the program, ratchets down every six months as roughly half of the RECLAIM firms transition from one compliance cycle to the next. The large increase in permits allocated in mid-1994 occurs because firms assigned to cycle 2 did not join the program until July. In 2000, the average rate of decline in permit allocations changes as the program transitions from firm-specific rates to a uniform rate of reduction in permit allocations.

The dashed line in figure 1 plots the permits allocated to firms reporting emissions in a given quarter. There are a number of reasons why not all firms receiving an initial permit allocation report emissions in all quarters. Some firms that received permit allocations initially were later exempted from the program following corrections to the data used to generate the original RECLAIM universe. Electricity generators were removed from the program in 2001 in the aftermath of the California electricity crisis. Other missing emissions observations are due to firm shutdowns, late reporting, or non-reporting (discussed in detail in Appendix 1). According to the annual program reports released by SCAQMD, none of the firms that ceased operations during the study period cited RECLAIM as contributing to the decision to close down.

It is instructive to compare the aggregate emissions cap over time with reported NOx emissions

[24] None of the facilities that were initially included in the RECLAIM universe, but ceased operations during the study period, have cited RECLAIM as a contributing factor in their decision to close (AQMD Annual reports 1994:2004).

(summed across reporting firms). The gray line in figure 1 plots NOx emissions that are reported and certified quarterly. If the emissions cap were binding and program compliance were perfect, we should expect aggregate emissions to be perfectly correlated with the emissions cap.[25] However, the correlation coefficient for the study period is 0.83. There are at least two explanations for this less-than-perfect correlation. First, the cap on emissions did not bind in the early years of the program. When designing the program, SCAQMD regulators anticipated that the aggregate cap would start to bind in 1996 or 1997 (Schubert and Zerlauth, 1999). Figure 2 suggests that this "cross-over" occurred in 1998.[26] Second, the program encountered non-compliance problems during California's electricity crisis in 1999-2000. During this period, several firms were unable to acquire sufficient permits to offset their emissions (SCAQMD, 2001). In 2001, electricity producers were categorically excluded from the RECLAIM program and subject to command-and-control regulation (SCAQMD, 2001).

Table 1 summarizes some defining features of firm-level permit allocations and some potentially important determinants of abatement choices and trading activity. Summary statistics are reported by compliance cycle. The quantity of permits allocated over the first decade of the program is approximately equally divided across the two cycles. This table shows that these observable characteristics, including the allocation parameters, historic emissions, and firm location, are not identically distributed across the two cycles.

Recall that the $P1$ parameter in equation (3) defines a firm's starting RTC allocation in the first compliance period. On average, these first allocations are larger among firms assigned to cycle 1. This is primarily due to the fact that baseline emissions are higher, on average, among

[25] Note that we would not necessarily expect a perfect correlation in emissions and the aggregate cap over time in a program that permits banking and borrowing of permits.

[26] Although the aggregate emissions cap did not start to bind until 1998, several individual facilities emitted at or in excess of their allocation in the early years of the program. (U.S. EPA, 2002). Interestingly, in the early years of the program, some facilities fell into non-compliance while other facilities let unused permits expire.

firms assigned to cycle 1. We obtained historic emissions measures for approximately 80 percent of the firms in our data. These are also summarized in table 1. Maximum historic emissions are strongly, but not perfectly, correlated with the $P1$ parameters (the correlation coefficient is 0.97).

The firm-specific rates at which permit allocations decrease over 1994-2000 varies significantly within, but not across, cycles. On average, the number of permits allocated to a firm decreased by 49 percent over the first seven years of the program and 61 percent over the first decade. Finally, the table reports the percentage of firms in each group located in the coastal "zone". In addition to a temporal designation, RTCs are also classified as "inland" or "coastal". Firms in the coastal zone cannot use permits purchased from an inland source to achieve compliance. Firms located in the inland zone face no spatial restrictions on their trading activities.[27] A larger share of cycle 2 firms are located in the more restricted coastal zone.

B Are the data consistent with the permit allocation rules?

Our research design relies to a significant extent on the manner in which permits were allegedly allocated in RECLAIM. It is therefore important to verify that the program data are consistent with the program rules as stated.

We begin by showing that the firm-level permit allocations are consistent with the allocation equations described in Rule 2002. Using the firm-specific $P1$ and $P2$ parameters and the equations described in AQMD rule, we construct annual permit allocations for each firm over the period 1994-2004.[28] When we regress observed permit allocations on our constructed values, the $R^2 > 0.99$

[27] The geography of the Los Angeles basin is such that emissions in the inland zone tend to stay inland, whereas emissions originating in the coastal zone can blow inland, thus exacerbating air quality problems in the inland region. Spatial trading restrictions are designed to limit the extent to which permitted emissions are concentrated disproportionately in the inland zone.

[28] More precisely, to construct our predicted allocation, we assume annual permit allocations decrease at facility specific rates (reductions of $\frac{(P1_i - P2_i)}{6}$), each compliance period over the years 1994-2000. Facility allocations then decrease at a common rate over the period 2000-2003. Allocations cease to decrease after 2003.

and the estimated coefficient on the predicted allocation variable is 0.99. The error term captures rounding errors and, in a very small number of cases, a discrepancy between our constructed values and observed allocations. In these few cases, the parameters defining a firm's allocation trajectory were adjusted in the years after the program began.[29]

Another important feature of the permit allocation process, and one that is essential to our identification strategy, is the random assignment of firms to compliance cycles. Under random assignment, observed and unobserved firm characteristics will be distributed equally in expectation across the two compliance cycles. In Table 1, we find that some important observable characteristics, including the allocation parameters and benchmark emissions, are not identically distributed across the two cycles. The industrial composition of the two groups also differs. We simulate the random allocation of firms to cycles 1000 times to determine the likelihood of observing differences at least as extreme as we observe. The observed differences in moments are all within one standard deviation of the simulated moments. We thus conclude that the observed permit allocations are consistent with the reported allocation methodology.[30]

C Summarizing the variation in permit allocations due to random cycle assignment

This subsection provides a more detailed explanation of how the random assignment of firms to different compliance cycles generates exogenous variation in firms' permit allocations.

Before the RECLAIM program got underway, firms were randomly assigned to one of two compliance cycles. On January 1 of calendar year y, the subset of firms assigned to cycle 1 begin

[29] Firms that disagreed with their initial permit allocation could appeal to have the allocations amended. Some requests to amend allocations were received as late as 1999.

[30] Using a simple t-test to assess whether the means of these two groups are statistically different from each, we also fail to reject the null of no difference.

compliance period y. Firms assigned to cycle 2 transition into compliance period $y-1$ on July 1 of calendar year y. Thus, random cycle assignment generates variation in the *timing* of permit allocations. It does not affect the quantity of permits a firm receives during any given compliance cycle.

Figure 2 illustrates how random cycle assignment affects the RTC allocation in aggregate. As in Figure 1, annual RTC allocations are spread equally across the four quarters of the corresponding compliance cycle. The solid line descending step function corresponds to cycle 1. The dashed line corresponds to cycle 2. Note that the number of permits allocated to cycle 1 firms in the first compliance period exceeds the number of permits allocated to cycle 2 firms. This is because, by chance, more emissions intensive firms were disproportionately allocated to the first compliance cycle (see table 1).

What we will be exploiting in our empirical analysis is the variation in timing induced by cycle assignment. On average, a firm's allocation of operable emissions permits is 15 percent larger in the first six months of each year if the firm is assigned to cycle 2 (as compared to the permit allocation it would receive under a cycle 1 assignment). In the second half of each year, all firms are operating within the same compliance period and permit allocations do not differ across cycle assignments.

To more explicitly illustrate the aggregate difference in permit allocations across cycles, we also plot the within time period, across cycle difference in allocations (subtracting permits allocated to cycle 1 firms from permits allocated to cycle 2 firms). Over much of the study period, permit allocations across cycles are roughly equal in the second half of each year when all firms are in the same compliance cycle. In the first 6 months of each year (when there is variation in compliance periods across cycles), the cycle 2 permit allocation exceeds that of cycle 1.

From an econometric perspective, the variation in permit allocations generated by the random assignment of firms to compliance cycles has strengths and limitations. A strength is that, by virtue of random assignment, observable and unobservable determinants of emissions will be identically distributed across compliance cycles in expectation. A limitation is that cycle assignment only manipulates the timing of a firm's permit allocation. It has no effect on other dimensions of the endogenous allocation variable that are potentially important from an applications perspective (such as the total number of permits allocated or the rate at which firm allocations decline over time). Fortunately, exogenous variation in the timing of permit allocations is a relevant dimension of variation in this policy context. Because permits cannot be moved from one compliance cycle to another, the timing of a firm's permit allocations is a potentially important determinant of emissions in the RECLAIM program.

If firms are taking advantage of the flexibility afforded by emissions permit trading, the timing of emissions reductions will depend on the aggregate emissions cap, but should not be affected by the firm's compliance cycle assignment. In contrast, if firms are pursuing an autarkic compliance strategy and adjusting emissions so as to stay within their allocated emissions limit, we should expect to see an effect of random cycle assignment on emissions when these limits bind. More precisely, we would expect to see the inter-cycle difference in emissions rising and falling with the inter-cycle difference in permits allocated. Figure 2 provides a preliminary look at this relationship and foreshadows some of our econometric results. We aggregate emissions across firms within a cycle at 6 month intervals. The dotted line in Figure 2 plots the intercycle difference. This figure provides no evidence of a correlation between differences in emissions and differences in permit allocations across compliance cycles.

5 Are emissions independent of the initial permit allocation?

This section is divided into three subsections. Subsection A presents the results from estimating several alternative specifications of equation (2). In subsection B we implement an instrumental variable strategy. Subsection C evaluates the robustness of the results. In all specifications, standard errors are clustered at the firm level so that they are robust against arbitrary heteroskedasticity and serial correlation (see Wooldridge 2002).

A Baseline specification

We start our testing for a causal relationship between a firm's initial permit allocation and firm-level emissions with a restrictive form of (2) that includes only the log of the initial permit allocation and time period fixed effects as covariates:

$$e_{it} = \phi A_{it} + \delta_t + \eta_{it}. \tag{4}$$

Our preferred unit of observation is firm-by-six-month periods. Biannual time periods are defined as January-June and July-December of each calendar year. Recall that staggered compliance cycles generates variation in permit allocations across six month periods, but not within. Each time a subset of firms transitions to a new compliance period (this occurs in January for cycle 1 and June for cycle 2), some subset of allocated RTCs cease to be valid, while another set of permits become eligible for use. Although permit allocations do not vary within a biannual time period, firm-level emissions and permit holdings do. Firms are required to demonstrate compliance (by offsetting emissions with permits) quarterly. As a robustness check, we will later report results using quarterly data.

Time fixed effects are included in equation (4) to capture the average effect of time varying determinants of emissions, including the aggregate emissions cap which is steadily tightening over the study period (see Figure 1). Even after controlling for the average downward trend in firm-level emissions, a strong, statistically significant relationship between initial permit allocations and firm-level emissions persists (regression 1 in table 2). This strong and positive correlation is consistent with findings documented elsewhere in the literature.

Of course, this strong positive correlation between emissions and the initial permit allocation need not imply causation. Specification (2) controls for some key factors that might determine both emissions and permit allocation. The allocation parameter $P1$ is used to proxy for historic emissions.[31] Ideally, we would also control for variation in abatement costs. These costs are notoriously difficult to measure directly. Instead, we include the difference in allocation parameters, $P1 - P2$ as a proxy for variation in expected compliance costs. Recall that permit allocations were reduced more (less) quickly among firms with ex ante expected low (high) abatement costs. When these variables are included, the estimate of ϕ remains positive and highly statistically significant (column 2 in table 2).

A third specification adds proxies for determinants of emissions that vary both over time and across firms. These include industry and county-specific wage measures, and industry-specific producer price indices. Because not all firms in the data can be mapped to unique industry identifiers, adding these variables to the estimating equation reduces the number of observations in the data. The inclusion of these variables does not significantly affect the parameter estimate of interest (column 3 in table 2).

[31] Alternatively, we could use the benchmark emissions measures that were used to calculate facility-specific allocation schedules. As noted in section 3, we could not obtain these measures for all facilities. Among the 80 percent of facilities for whom we could obtain these measures, the correlation between benchmark emissions and the initial allocation parameter ($P1$) is 0.97

Because permit allocations in RECLAIM vary not only across firms, but also across time within firms, we can include firm-level fixed effects in the estimating equation, thus purging our estimates of the effects of time-invariant factors that determine both permit allocations and emissions. These inclusion of these fixed effects significantly improves the fit of the model. The fixed-effects estimate of ϕ is 0.49 with a standard error of 0.13. Although this point estimate is somewhat smaller than the estimates reported in columns 1 through 3, it remains highly significant and positive. If this fixed effects regression estimate identifies the causal effect of the initial allocation on emissions, a 1 percent increase (decrease) in a firm's permit allocation leads, on average, to a 0.5 percent increase (decrease) in emissions.

Recall that firm-specific permit allocations decrease at a common rate over the period 2001-2003. This stands in contrast to 1994-2000 when the rates at which a firms' allocations decrease reflects firms' anticipated abatement costs, operating characteristics, and past emissions. If the statistically significant allocation coefficient reported in column (4) is capturing the effect of the omitted variables that determine both permit allocations and emissions (versus a causal relationship between permit allocations and emissions), this effect should disappear during the 2001-2003 period. As a robustness check, we estimate the fixed-effects regression specification using only data from the period 2001-2003. Using this restricted sample, we obtain a point estimate of -0.01 with a standard error of 0.55. Unfortunately, using data from only three years reduces the number of observations by over 70 percent; so this estimate is very imprecise. Although we cannot conclude anything from such a noisy estimate, the estimate suggests that the statistically significant fixed effects estimate of ϕ may be capturing the effect of omitted variables, versus the direct effect of variation in RTC allocations, on emissions.

B Instrumental Variables Estimates of the Relationship Between Initial Permit Allocations and Emissions

As discussed in Section 2, we cannot assume that fixed effects are a panacea for omitted variables bias in this context. Fortunately, as we discuss in Section 4, random assignment of firms to compliance cycles generates exogenous variation in the timing of firms' permit allocations. We use this variation to instrument for firm-level permit allocations.

For expositional purposes, we define assignment to cycle 1 as the "control" assignment, whereas assignment to cycle 2 is defined as the "treatment". Recall that assignment to the treatment cycle affects the number of operable permits allocated to a firm in the first half of every calendar year. We construct our instrument Z_{it} by interacting a cycle 2 indicator variable (which equals one if firm i is assigned to cycle 2) and a dummy variable that equals one if time period t corresponds to the first, versus the second, half of a calendar year.

When implementing the IV estimation, we focus our attention on specifications (2) and (3) in table 2.[32] Our preferred specification (3) includes both time and firm fixed effects. The corresponding first stage (denoted by F) is:

$$A_{it} = \alpha_i^F + \gamma Z_{it} + \delta_t^F + u_{it},$$

where the A_{it}, α_i and δ_i are defined as in section 2.

In principle, we need not include covariates or fixed effects in this IV framework. In expectation, randomization ensures that observable and unobservable determinants of emissions are

[32] The wage and producer price indices are not found to be significant determinants of facility-level emissions in any specifications that include time fixed effects. Moreover, to include these variables we must drop the 20 percent of facilities (on account of missing data or affiliation with multiple industrial classifications). We thus exclude these variables from our preferred specifications.

uncorrellated with cycle assignment. However, our sample size is fairly small. In small samples, simple randomization methods (such as were used here) can result in imbalanced covariates among treatment and control groups. In fact, across the two cycle assignment groups, we observe some imbalance in prognostically important covariates (see Table 1). Although this imbalance occurs by random chance, it can still confound inference if not properly accounted for. Including fixed effects and/or covariates in the estimating equation helps to compensate for the imbalance that we observe. The firm-level fixed-effects are particularly effective in reducing the unexplained variance in the emissions outcomes, thus improving the precision of our IV estimates.

Panel A of table 3 shows a strong first-stage relationship between the instrument and firm-level permit allocations. The coefficient on the instrument, γ, has an intuitive interpretation. It captures the average effect, in percentage terms, of the cycle 2 assignment on firms' permit allocation in the first half of each year.[33] This relationship is particularly strong in the specification that includes firm fixed effects, with a t-statistic of more than 16. The F-statistic on the excluded instrument, a standard measure of instrument relevance, is also substantially larger when we include fixed effects to reduce the residual variance. However, in both specifications, the proportion of the variability in the endogenous variable that is explained by the excluded instrument (summarized by the partial R^2) is low.

Panel B reports the IV estimates of the permit allocation coefficient ϕ. In both specifications, we fail to reject the null hypothesis that the allocation coefficient is zero. The estimate in column 1 is imprecise. In column 2, the inclusion of fixed effects reduces the variance of the IV estimator somewhat. The preferred IV estimate of ϕ is -0.11 with a standard error of 0.32. Two standard error bands of this estimate exclude the OLS estimates of ϕ and almost exclude the FE estimate.

[33] This is equivalent to the average percentage difference-in-difference in biannual permit allocations. The first difference is taken across the first and second half of each year. The second difference is taken across facilities assigned to cycles 1 and 2.

These results suggest that the positive, statistically significant correlation between the initial permit allocation and firms' emissions is capturing the effect of the endogenous component of permit allocation schedules—the portion that is based on firm-specific operating characteristics and anticipated abatement cost trends —rather than a causal relationship between permit allocations and emissions per se.

The lack of precision in these IV estimates warrants concern and raises questions about whether the potential for omitted variables bias justifies the substantial loss of efficiency. Unfortunately, in situations such as this where testing for the existence of an endogeneity problem is particularly important, tests of the null hypothesis of no endogeneity can be misleading. Nakamura et al. (1998) note that when the proportion of the variability in the endogenous variable that is explained by the excluded instrument is low, the power of endogeneity tests is low and type II error rates are high. Thus, when the partial R^2 on the excluded instrument is low (as it is in our case), researchers are cautioned against using endogeneity testing as a means of deciding whether to instrument for a potentially endogenous right-hand side variable. Nevertheless, these tests can be informative. We conduct an endogeneity test of the null hypothesis that the specified endogenous regressors can actually be treated as exogenous. The p-value of the chi-square test statistic is 0.06. We reject the null hypothesis at the 10 percent level, but not the 5 percent level.

A weak rejection of the null hypothesis of no endogeneity (which is notable given the power properties of the test when the partial R-squared is so low) and strong a priori reasons for believing that firm-level permit allocations are correlated with the residual in the estimating equation lead us to conclude that instrumenting for permit allocation is important and worthwhile. Based on our IV estimation results, we fail to reject the hypothesis that firm-level emissions in RECLAIM are independent of the initial distribution of permits.

C Robustness checks

Table 4 investigates the robustness of the results. Columns 3-4 demonstrate robustness to using data aggregated quarterly. Firms are required to report emissions and certify compliance quarterly. Estimating the model using quarterly data also allows us to use a larger data set; aggregation to biannual time periods forces us to drop observations because we require that a firm report emissions in both quarters of a given six month period. When the model is estimated using quarterly data, our results are virtually unchanged. Slight differences are likely due to the slightly larger sample.[34]

Colums 5-6 report results for a balanced panel of firms. The panel we use to generate estimates reported in tables 2 and 3 is unbalanced. The maximum number of biannual emissions reports is 22 for cycle 1 firms and 21 for cycle 2 firms (these firms enter the program in July of 1994). On average, cycle 1 (cycle 2) firms report emissions in 15 (14) periods. If plant exit and/or misreporting is non-random, this can introduce bias into our results. Absent a credible exclusion restriction, the standard Heckman selection correction is uninformative.[35] A less satisfying approach to testing the implications of unbalanced panel data involves checking whether the exit of firms might be affecting the results . Columns 5 and 6 of table 5 report results from re-estimating the model using data from the 87 firms that report emissions in all quarters. Although these estimates are qualitatively consistent with our main results, the dramatic reduction in sample size significantly impacts the precision of the estimates.

[34] We also estimate a model that does not include facility-fixed effects using data aggregated annually. These results are qualitatively consistent with our analysis that uses quarterly and bianual data, although the results are quite imprecise. This occurs for two reasons. First, annual aggregation reduces the number of observations because we can only use observations for a given facility and year if the facility has reported emissions in all four quarters. Second, we can no longer include facility-fixed effects in the IV specification when the model is used using annual data.

[35] Ideally, we would have an instrument that significantly determines selection into our sample, but can be credibly excluded from the outcome equation.Unfortunately, we were unable to find such a variable. Indeed, we doubt that such a variable exists.

6 Summary and conclusions

A particularly appealing aspect of the "cap and trade" approach to regulating industrial emissions is that, provided certain assumptions are met, the market will direct those firms with the lowest abatement costs to reduce emissions, regardless of how permits are initially allocated. This important claim has been extremely difficult to directly test because of the likely endogeneity of firm-level permit allocations with respect to emissions.

In Southern California's Regional Clean Air Incentives Market, market participants were randomly assigned to different permit allocation cycles. We use this random assignment to instrument for endogenous firm-specific permit allocations. Notably, when we do not instrument for permit allocations, we do find evidence of a strong correlation between emissions and allocations. This could could indicate a direct, causal relationship between permit allocations and emissions, or this could reflect a statistically significant correlation between emissions and the endogenous component of permit allocation schedules. More careful analysis lends support to the latter hypothesis. Our IV estimate (presumably free of omitted variables bias) is not statistically significant. Based on these results, we cannot reject the hypothesis that nitrogen oxide emissions at RECLAIM firms were independent of how emissions permits were allocated across firms.

Our results lend empirical support to the hypothesis that emissions in equilibrium are independent of how emissions permits are initially allocated across firms. This hypothesis is an important component of the theoretical foundations underlying market-based pollution permit trading programs. That said, we hesitate to draw broad, definitive conclusions from these findings. It should be reiterated that our identification strategy is somewhat limited because we can only credibly test for a relationship between emissions and the kind of variation in firms' permit allocations that is induced by random assignment to allocation cycles. Thus, our results pertain to the effects of relatively short-run changes in emissions permit allocations. Moreover, the lack of precision in the IV estimates warrants some concern. We cannot confidently rule out all economically significant positive effects of permit allocations on emissions. Further empirical testing of the independence of emissions and permit allocations is certainly warranted. Unfortunately, the paucity of truly exogenous variation in emissions permit allocations will likely make this difficult to implement.

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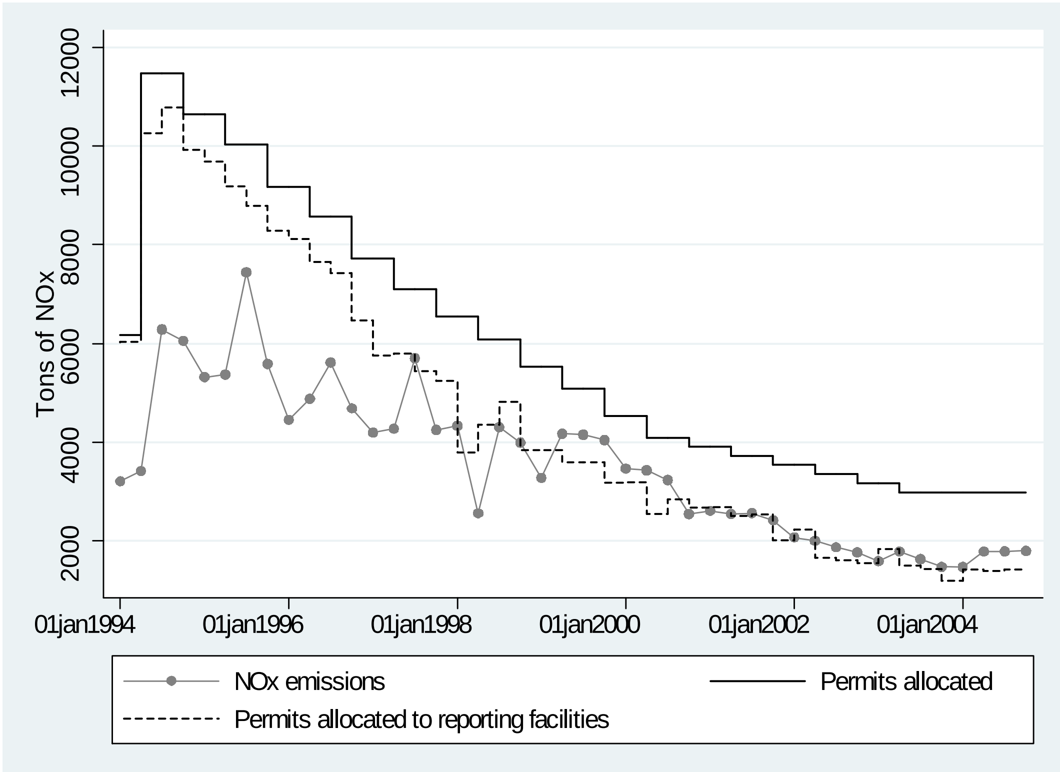

Figure 1: The Emissions Cap and Observed Emissions in Southern California's RECLAIM Program: 1994-2004

Notes: This figure plots quarterly emissions and RTC allocations over the period 1994-2005. Permit allocations and emissions are measured in tons of nitrogen oxide.

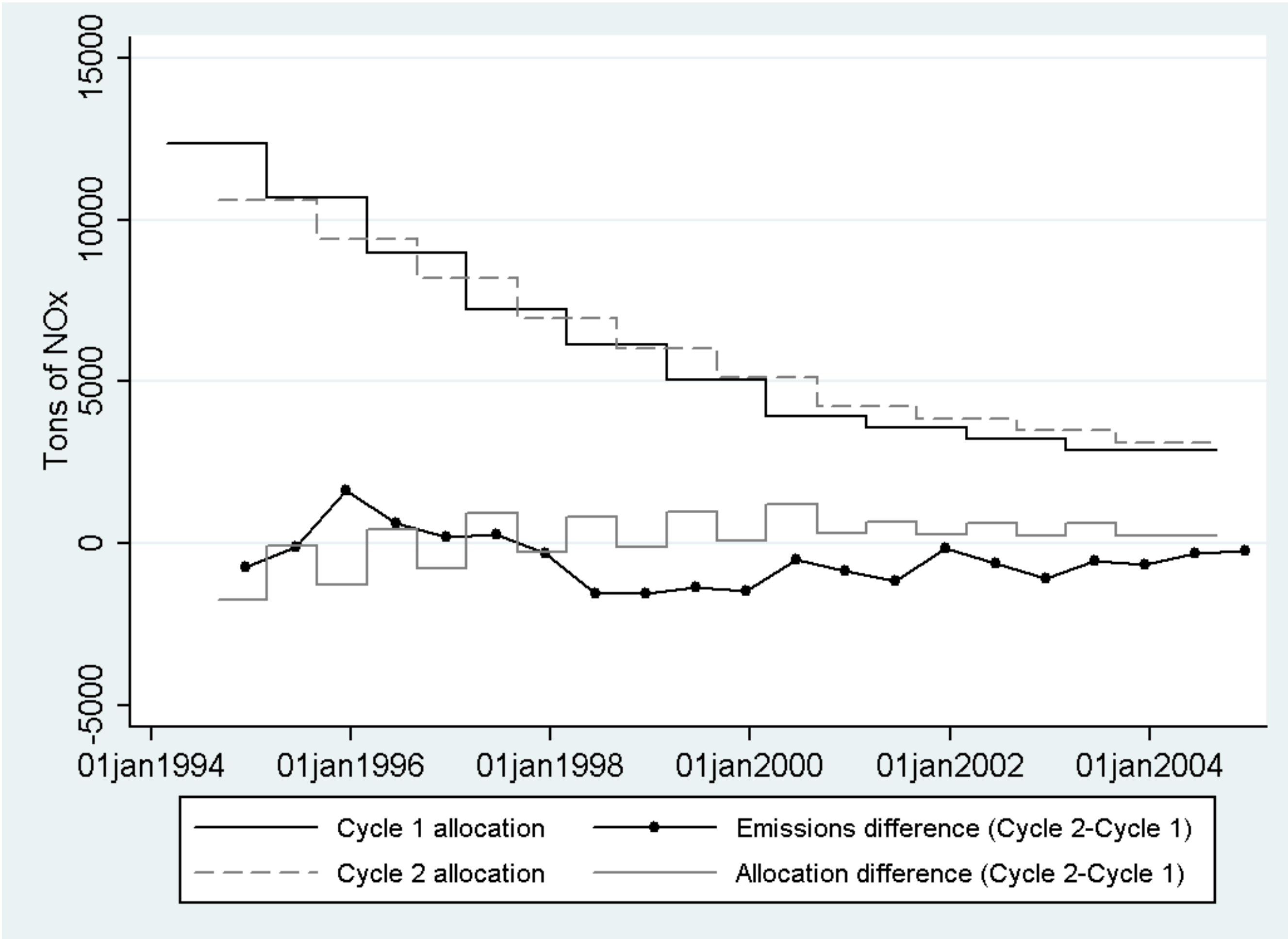

Figure 2 : Permits (levels and differences) and Emissions (differences) across Compliance Cycles

Notes: The upper step functions plot RTC permit allocations by allocation cycle. The bottom two lines plot differences in permit allocations across allocation cycles and differences in emissions across allocation cycles.

Table 1 : Permit Allocation Parameters by Compliance Cycle

VARIABLE	Allocation cycle 1	Allocation cycle 2
$P1$ RTC allocations in the first cycle (tons of NOx)	130 (318)	103 (342)
Historic maximum emissions (tons of NOx)	151 (387)	116 (400)
$(P1 - P2)/P2$ % reduction in quarterly allocations	49% (30%)	48% (28%)
% of permits allocated 1994-2003	52%	48%
Coastal trading zone	71%	76%
Number of firms	173	204

Notes: This table reports summary statistics for parameters that describe facility-specific permit allocation schedules by compliance cycle. Standard deviations are in parentheses.

Table 2 : Cross-Sectional and Fixed Effects Estimates of the Effect of Permit Allocation on Emissions

	Pooled OLS (1)	Pooled OLS (2)	Pooled OLS (3)	Fixed effects OLS (4)
	Dependent variable: log emissions			
Log permit allocation	0.79*** (0.05))	0.65*** (0.14)	0.65*** (0.17)	0.49*** (0.13)
Log wage			-0.24 (0.17)	
Log Producer price index			0.36 (0.28)	
log allocation in first compliance period ($P1$)		0.14 (0.15)	0.18 (0.19)	
log change in allocation ($P1 - P2$)		0.00 (0.03)	0.03 (0.05)	
firm fixed effects	no	no	no	yes
$R-squared$	0.46	0.46	0.49	0.78
Root mean square error	1.42	1.42	1.34	0.90
firms	361	360	291	361
Observations	5190	5168	3760	5190

Notes: Robust standard errors clustered by facility are in parentheses. Time-period fixed effects are included in all specifications (coefficients not reported). * Significantly different from 0 at 90 percent confidence. ** Significantly different from 0 at 95 percent confidence *** Significantly different from 0 at 99 percent confidence

Table 3 : Instrumental Variables Estimates of the Effect of Permit Allocation on Emissions

	IV-2SLS	Fixed effecs IV-2SLS
	(1)	(2)
Panel A: Dependent variable is log permit allocation		
Cycle 2 * Jan-July indicator	0.19***	0.12***
	(0.04)	(0.01)
Partial F-statistic	20.47	268.05
Partial $R-$squared	0.02	0.01
Panel B: Dependent variable is log emissions		
Log of permit allocation	−0.13	-0.11
	(0.62)	(0.32)
Root mean squared error	1.46	0.92
firms	360	361
Observations	5168	5190

Notes: Robust standard errors clustered by facility are in parentheses. Time-period fixed effects are included in all specifications (coefficients not reported). * Significantly different from 0 at 90 percent confidence. ** Significantly different from 0 at 95 percent confidence *** Significantly different from 0 at 99 percent confidence

Table 4 : Assessing the Robustness of the Allocation Effect Estimates

	Benchmark		Quarterly data		Balanced Sample	
	Fixed effects OLS (1)	Fixed effects 2SLS (2)	Fixed effects OLS (3)	Fixed effects 2SLS (4)	Fixed effects OLS (5)	Fixed effects 2SLS (6)
	Dependent variable is log emissions					
Log permit allocation	0.49*** (0.13)	−0.11 (0.32)	0.46*** (0.13)	−0.06 (0.31)	0.59*** (0.19)	0.07 (0.35)
Partial F-statistic (first stage)	–	268	–	435	–	166
$R - squared$	0.78	–	0.78	–	0.82	–
firms	361	361	377	377	87	87
Observations	5190	5190	10,547	10,547	1860	1860

Notes: Robust standard errors clustered by facility are in parentheses. Time-period fixed effects are included in all specifications (coefficients not reported). * Significantly different from 0 at 90 percent confidence. ** Significantly different from 0 at 95 percent confidence *** Significantly different from 0 at 99 percent confidence

7 Appendix

We submitted a SCAQMD public records request to obtain firm-level information about firm location, compliance cycle assignment, operating characteristics, emissions, and RTC allocations. We linked these data with price data from other sources. Our data set contains firm-level information from the first quarter of 1994, the beginning of the RECLAIM program, through 2004. We have also obtained information on the data that were used to determine initial allocation schedules. Because we are interested in the relationship between permit allocations and emissions, only those firms that receive RTC allocations are included in this study.[36]

Quarterly emissions

All RECLAIM firms are required to submit quarterly emissions reports to SCAQMD. On average, there are 30 quarterly emissions reports per firm (of a possible 44 quarters for cycle 1 firms, and a possible 42 quarters for cycle 2 firms).

There are several reasons why emissions reports are not available for some firms for all possible quarters. In the early years of the program, several of the original firms dropped out of the RECLAIM program. Some firms closed down for reasons unrelated to the RECLAIM program or were found to be exempt from RECLAIM after adjustments of initial emissions calculations revealed that the firms produced fewer than the limit of four tons/year (Lieu et al., 1998). In addition, emission data are missing in some quarters because of malfunctioning emissions monitoring equipment or late reporting. If emissions are transmitted after the deadline, the report is rejected and recorded as missing.[37]

There may be measurement error in the emissions data for smaller pollution producers. For monitoring and reporting purposes, RECLAIM sources are divided into four categories: major sources, large sources, NOx process units, and designated equipment. A firm can have anywhere from 1 to 144 monitored sources. Major sources, which account for 14 percent of RECLAIM NOx sources, are required to install a continuous emissions monitoring system to measure emissions directly. Large sources (approximately 20 percent of RECLAIM NOx sources) have the option to be monitored by a continuous process monitoring system (which uses emissions factors or rates to estimate total emissions). The NOx process units (57 percent of NOx sources) and designated

[36] Only the original firms—those present when the program began in 1994—received quarterly allocations. Any new firms entering SCAQMD that are NOx emitters must either purchase credits to cover their emissions or, in some cases, take advantage of a special reserve of RTCs earmarked for job-creating, clean companies (Schwarze et al., 2000).

[37] This is based on personal correspondence with George Haddad of SCAQMD (2002).

equipment (9 percent), are allowed to impute their emission using measures of fuel consumption, processing rate, or operating time in conjunction with an emission factor or emission rate.

Permit allocations

SCAQMD maintains a database tracking all NOx permits. This database contains initial RTC allocations, allocation adjustments, retirements, and trades (measured in pounds). From these data, we recovered the NOx permit allocation schedule for 384 RECLAIM firms. Any certified adjustments that were made by SCAQMD after the allocations were initially determined are incorporated into our measure of allocation.

Producer prices

Using the information SCAQMD provides about the identity of RECLAIM firms, we determined the four-digit North American Industry Classification System (NAICS) code for each firm. RECLAIM firms fall into 144 different industrial classifications. Because we could not obtain firm-level data on revenues or product prices, we used the Bureau of Labor Statistic's four-digit NAICS and SIC Producer Product Indexes (PPI) as a proxy for shifts in product demand facing firms. There are several industrial classification categories for which producer price series could not be found, including finance, insurance, real estate, entertainment, and public administration categories.

Wages

Industry-specific wages at the county level are obtained from the US Census Bureau's County Business Patterns. All prices are adjusted to 2000 constant dollars. As with producer prices, facilities are matched with wage data using industrial classification codes.