Correct (and misleading) arguments for cap and trade*

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Abstract

Cap and trade (CAT) results in lower abatement costs relative to command and control, but might increase industry marginal abatement cost, resulting in higher equilibrium emissions. With lumpy investment, command and control leads to multiple investment equilibria and "regulatory uncertainty". CAT, a first best policy, eliminates this uncertainty. Command and control policies cause firms to imitate other firms' investment decisions, leading to similar costs and small potential gains from permit trade. CAT induces firms to make different investment decisions, leading to different abatement costs and large gains from trade. In a "global game", the unique equilibrium is constrained socially optimal.

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1 Introduction

Two differences between non-tradable emissions ceilings (hereafter, "command and control") and cap and trade (CAT) appear to have gone unnoticed: (i) Although CAT, a first best market based policy, reduces the social abatement cost, compared to inefficient command and control policies, the former does not globally reduce the *marginal* social abatement cost. The socially optimal level of emissions might be higher under either policy. Economists should be cautious of selling market based policies such as CAT as environmentally-friendly. (ii) When the current policymaker cannot commit to future policy levels, and firms make lumpy investment decisions affecting their future abatement costs, command and control policies create multiple competitive equilibria. To an individual firm, this multiplicity induces regulatory uncertainty even without intrinsic uncertainty. In the same circumstance, CAT induces a unique socially optimal equilibrium, with no regulatory uncertainty.

Here I outline the deterministic model and discuss its assumptions. I use California (Assembly Bill) AB32 to illustrate the analysis's relevance, but do not tailor the model to this bill. In a first period, atomistic and homogenous firms decide to either invest in a new technology, reducing their future abatement costs, or to keep their current technology. They know the second period policy instrument, either CAT or command and control. Under both policies, a firm's permit allocation does not depend on their investment decision. Firms cannot trade permits under the command and control policy. In the second period the regulator sets the number of permits at the optimal level, conditional on the exogenous policy instrument and the endogenous investment decisions.

Although abstract, this model helps study many environmental policy problems, e.g. AB32. There was sharp disagreement about implementation policies before the bill's passage. The text of the bill refers to market based policies, without naming these and without prejudging their adoption. Opposition to these polices was based on mistrust of markets, or on second-best arguments such as the possibility markets would create high local concentrations ("hotspots"). Despite the extensive academic research comparing market based and command and control policies, the literature has ignored the issues explored here.

I assume the second period level of emissions permits is conditioned on aggregate investment decisions, but AB32 stipulates unconditional targets. However, Article 3859 gives the Governor the right to adjust the targets "in the event of extraordinary circumstances, catastrophic events, or the threat of significant economic harm." The third contingency includes the possibility that abatement is much more expensive than anticipated at the bill's passage. The eventual abatement cost depends in part on aggregate investment, as in my model. In 2010 a well-financed but unsuccessful referendum attempted to suspend AB32. Although policymakers can announce future unconditional emissions levels, the policy levels implemented will likely be conditioned on future events, some of which are endogenous. I assume the policy instrument (here, CAT or command and control) is exogenous. AB32 left the implementation policy to the discretion of future policy makers, who subsequently (substantially) decided in favor of CAT. The important point is that selecting the policy instrument precedes a significant portion of investment.

Firms in my model are atomistic, and except for the paper's final section, homogenous. The atomistic assumption means firms do not invest strategically, e.g. to influence the regulator. Perhaps in some markets firms invest strategically with respect to regulators; many papers assume that they do (see below) but I have not found empirical evidence of this behavior. In prominent oligopoly models (e.g. Cournot competition, homogenous products), the equilibrium is sensitive to the number of firms when there are only a few firms, and rapidly approaches the competitive level with more than several firms. In this case, the competitive equilibrium may be a reasonable approximation even with strategic firms. The atomistic assumption is, at least, a useful starting point. Actual firms differ across many characteristics prior to making investment decisions. The paper's final section introduces firm heterogeneity.

The regulator who uses non-tradable permits would like to give fewer licenses to firms that invested and consequently have lower marginal costs, but I assume she must give each firm the same number of permits. The regulator commits to the uniformity but not the level of the policy. In private conversations, policy advisors active in Canada described the political uproar following the possibility that Canada would impose stricter standards on firms that had made investments with a view to decreasing the cost of anticipated regulations. A policy rewarding a firm for not making investments that lower its abatement costs is obviously perverse. Many policies include grandfather provisions that do reward past emissions, but those emissions were almost certainly not motivated by the desire to obtain larger future allowances. The question here is whether a politically reasonable policy design enables firms to use investment to manipulate future emissions allowances, in a manner that reduces social welfare. The uniformity assumption excludes this possibility. Uniformity also lowers the policy's informational requirement.

I now briefly explain the results. CAT leads to the first best outcome even with lumpy investment: the socially optimal fraction of firms adopt the new technology, they trade permits, and all emit at the optimal level. This result provides a benchmark. CAT encourages similar firms to make different investment decisions, increasing the differences in firms' abatement costs and thereby increasing the efficiency gains from trade in permits. A command and control policy, in contrast, encourages similar firms to all make the same investment decision, thereby preserving firm homogeneity. Thus, a command and control policy may appear to cause little efficiency loss, because in equilibrium there would be little trade even if it were allowed. However, this firm homogeneity may be a consequence of the anticipated lack of opportunity for trade. The efficiency gains from CAT include the effect of the policy regime on the aggregate investment decisions.

Some contingencies affecting future policies are endogenous to the economy, but exogenous to individual firms. The socially optimal future abatement level depends on the future abatement costs, which depend on earlier investment decisions. The anticipation that the regulator will use non-tradable permits induces a coordination game among firms at the investment stage. Firms know that investment by a larger fraction of firms reduces the industry marginal abatement cost curve, reducing the second-stage emissions allowance and increasing the value of investment. Thus, the post-investment allocation of non-tradable permits makes the investment decisions strategic complements. With *ex ante* identical (more generally, similar) firms, there are two rational expectations competitive equilibria: all firms invest or none of them do. This multiplicity of equilibria creates "strategic uncertainty": firms cannot predict industry behavior and therefore cannot predict the regulator's behavior. From the standpoint of the individual firm this strategic uncertainty looks like regulatory uncertainty.

In contrast, under CAT there is a unique rational expectations competitive equilibrium. An increase in the fraction of firms that invest reduces the equilibrium (regulator-determined) supply of permits. However, the increased investment also lowers the equilibrium price of tradable permits, thus reducing the value of the investment for any firm. The investment decisions are therefore strategic substitutes, leading to a unique, socially optimal equilibrium to the investment game. Rational firms can predict the second stage permit price; the commitment to use CAT eliminates regulatory uncertainty.

CAT and command and control policies induce different investment equilibria, which by itself leads to different emissions equilibria. The conclusion that first best market based policies might not be environmentally friendly reflects a different consideration, deserving emphasis. For a given level of investment, it is strictly cheaper to achieve (almost) any abatement level using efficient rather than inefficient policies, an observation that makes the former appear environmentally friendly. Of course, the equilibrium abatement level depends on social marginal rather than total costs. Total costs equal the integral of marginal costs, so efficient policies must reduce (relative to inefficient policies) marginal costs at least over some interval. But efficient policies, in general, need not globally reduce marginal costs, and therefore need not increase the equilibrium abatement level, conditional on previous investment.[1]

The paper's final section considers different kinds of firm heterogeneity, arising either from different characteristics (e.g. firm-specific investment costs) or different information. The results described above are robust to firm-level differences in characteristics. A generalization that allows firms to be uncertain about the type of post-investment environmental policy (given common beliefs) is also straightforward.

The more interesting generalization arises if each firm receives a private signal about a market fundamental before investment. For example, firms learn their own investment cost, a signal that tells them something about average industry investment costs; here firms do not have common knowledge. Investment decisions are strategic complements under common knowledge, when the second period policy is command and control. Readers familiar with global games will not be surprised that an arbitrarily small amount of post-signal uncertainty induces a unique equilibrium to the investment game (Carlsson and Van Damme 1993), (Morris and Shin 2003). The new, and I believe surprising result is that this unique equilibrium is constrained socially efficient. An arbitrarily small amount of post-signal uncertainty about market fundamentals not only eliminates the multiplicity of equilibria (the known result), but also insures that the resulting equilibrium investment level is the same as the social planner would choose (the new result). This conclusion holds even though the social planner wants to minimize the sum of abatement and investment costs and environmental damages, while firms care only about their private abatement and investment costs. However, the uniqueness result does not survive the introduction of public information.

In summary, in addition to the (not surprising) result that CAT is efficient even with lumpy investment, the paper shows that CAT reduces (relative to command and control

[1] Most counterintuitive results are special cases of the Theory of the Second Best, and that is also (vacuously) true here. However, the result appears to have baffled some audiences. In a conference call with a group of State of California economists who were tasked to develop implementation policies for AB32, the claim met considerable resistance. The belief that the cost reductions resulting from the use of efficient policies lead to higher abatement seems widespread. For example, an expert group involved with designing California's environmental policy writes, "Properly structured market mechanisms can reduce the costs associated with emissions reductions and climate change mitigation while reducing emissions beyond what traditional regulation can do alone." (Economic and Technology Adancement and Advisory Committee 2008), page 2.

policies) regulatory uncertainty and leads to greater post-investment firm cost heterogeneity – and therefore greater gains from subsequent permit trade. However, economists should not promote CAT (e.g. to environmentalists) on the grounds that it induces larger equilibrium abatement. That claim can be false.

Jaffe, Newell, and Stavins (2003) and Requate (2005) survey the literature on pollution control and endogenous investment. Many papers in this literature, including Biglaiser, Horowitz, and Quiggin (1995), Gersbach and Glazer (1999), Kennedy and Laplante (1999), Montero (2002), Fischer, Parry, and Pizer (2003), Moledina, Polasky, Coggins, and Costello (2003), Tarui and Polasky (2005) and Tarui and Polasky (2006) assume firms behave strategically with respect to the regulator. Malueg (1989), Milliman and Prince (1989), Requate (1998), and Requate and Unold (2003) treat firms as non-strategic. A related literature discusses the effect of regulation on technology development (Popp 2006), (Jaffe and Palmer 1997), (Newell, Jaffe, and Stavins 1999), (Taylor, Rubin, and Hounshell 2005) or investment in abatement capital (Karp and Zhang 2012). None discuss multiple competitive equilibria under command and control, so they do not consider the relation between the policy instrument and regulatory uncertainty, or between the policy instrument and the equilibrium abatement level; nor do they consider the global game application.

2 The model

Each identical firm, facing no exogenous uncertainty, decides whether to upgrade its plant ($K = 1$) or to keep its current plant ($K = 0$). The firm's decision determines its second period abatement cost function. Firms' aggregate decisions determine industry-wide abatement costs. In the second period, the regulator chooses the number of emissions permits allocated to each firm (the same for each firm), to minimize the sum of abatement costs and environmental damage. At the investment stage, firms know the second period policy regime, which either allows or prohibits trade in permits. Absent investment and abatement, each firm emits e^{BAU}. For emissions $e \leq e^{BAU}$, second period abatement equals $a \equiv e^{BAU} - e$. The firm's abatement cost, $\tilde{c}(a, K)$, is increasing and convex in abatement. Investment decreases both abatement costs and marginal abatement costs.

The firm's benefit of emissions, $c(e, K)$, equals the negative of abatement costs: $c(e, K) \equiv -\tilde{c}(a, K)$. The firm's marginal benefit of emissions equals $c_e(e, K) \equiv \tilde{c}_a(a, K)$, the marginal abatement cost. The assumptions above imply $c(\cdot)$ is increasing and concave in e and decreasing in K, with $c_e(e, 1) - c_e(e, 0) < 0$. This inequality implies the cost minimizing level of emission, which satisfies $c_e(e, K) = 0$, decreases in K. The firm's investment cost equals ϕ, and κ equals the fraction of firms that invest, $0 \leq \kappa \leq 1$. If $0 < \kappa < 1$, firms are heterogenous in the second stage, when the regulator chooses the level of pollution permits.

Each firm receives the emissions allowance e, independently of whether it invested. The mass of firms equals 1, so aggregate emissions equal e. The damage function is $D(e)$, an increasing convex function. If trade occurs, firms emit at different levels. If firms that did not invest ($K = 0$) emit e^0 and firms that did invest ($K = 1$) emit e^1, total emissions are $(1 - \kappa) e^0 + \kappa e^1 = e$ and social costs (abatement costs plus investment costs plus environmental damages) equal

$$P\left(e^0, e^1, \kappa\right) \equiv -\left(1 - \kappa\right) c(e^0, 0) - \kappa c(e^1, 1) + \kappa\phi + D(e). \tag{1}$$

Firm-level investment is lumpy, but because firms are individually small, investment appears smooth at the societal level. Subscripts denote partial derivatives and superscripts $0, 1$ identify the firm's investment decision.

3 The abatement stage

Trade in permits has counteracting effects on the marginal social value of an additional unit of emissions, and might either increase or decrease the socially optimal emissions level for a given κ. Throughout this section I take κ as predetermined, with $0 < \kappa < 1$; trade is not interesting if all firms are identical.[2]

Trade reduces abatement costs, a fact that promotes higher abatement (lower emissions). But trade allocates an additional emissions unit optimally, a fact that tends to increase the social marginal value of additional emissions. Either of these effects might dominate. Because trade reduces industry abatement costs for all levels of abatement, it must lower industry *marginal* abatement costs for *some* abatement levels. However, if the industry marginal abatement cost curves with and without trade cross, then the location of the marginal damage curve determines whether trade increases or decreases equilibrium abatement.

Without trade, all firms emit at the same rate: $e^0 = e^1 = e$. Given κ, the first

[2] The results of this section depend on the assumption that the regulator chooses the number of permits to minimize social costs. If, alternatively, the regulator chose the maximum level of abatement subject to a cost constraint, permit trade always increases the amount of abatement.

order condition for the minimization of social costs, $P(e,e,\kappa)$, is

$$D'(e) = (1-\kappa)\,c_e(e,0) + \kappa c_e(e,1). \tag{2}$$

Previous curvature assumptions guarantee the second order condition, $S \equiv \frac{d^2P(e,e,\kappa)}{de^2} > 0$. Equation (2) implicitly defines the socially optimal no-trade emission level, e^{NT} (NT for "no trade") as a function of κ: $e^{NT} = e(\kappa)$.

With trade, I say a level of permits e induces an *interior* trade equilibrium if the permit price is positive and low cost firms do not sell all their permits. At an interior equilibrium, trade equates investors' and non-investors' marginal costs, and the permit price equals this marginal cost. Denote e^t as the purchases per non-investor ($K=0$). The mass of purchases equals $(1-\kappa)\,e^t$, so permit sales per low cost firm ($K=1$) equal $\frac{(1-\kappa)e^t}{\kappa}$. At an interior equilibrium, given the allowance e, the conditions that determine quantity traded (e^t) and permit price (p) are

$$c_e\left(e+e^t,0\right) = c_e\left(e - \frac{(1-\kappa)\,e^t}{\kappa},1\right) \text{ and } c_e\left(e+e^t,0\right) = p(e,\kappa). \tag{3}$$

The first of these equations implicitly defines the function $e^t = e^t(e;\kappa)$. The equilibrium is interior if and only if

$$c_e\left(e+e^t(e;\kappa),0\right) > 0 \;\text{ and } e - \frac{(1-\kappa)\,e^t(e;\kappa)}{\kappa} > 0. \tag{4}$$

Given κ, the planner's problem is to choose e to minimize

$$W(e;\kappa) = -(1-\kappa)\,c\left(e+e^t,0\right) - \kappa c\left(e - \frac{(1-\kappa)\,e^t}{\kappa},1\right) + D(e).$$

(Recall: $c(e,K)$ is the benefit of emissions, a concave increasing function.) I strengthen previous curvature assumptions, adopting

Assumption 1 *$W(e;\kappa)$ is convex in e:* $S^t \equiv \frac{d^2W}{de^2} > 0$.

Using equations (3), the first order condition is

$$D'(e) = (1-\kappa)\,c_e\left(e+e^t,0\right) + \kappa c_e\left(e - \frac{(1-\kappa)\,e^t}{\kappa},1\right) = p(e,\kappa). \tag{5}$$

To produce a unified treatment, I define the trivial function $e^n(e;\kappa) \equiv 0$, the level of trade when there is *no* trade. The individual firm's marginal benefit of emissions equals its marginal abatement cost. The social marginal benefit of emissions, $G(e;\kappa,j)$, $j =$ *trade, no trade,* equals the *industry* marginal abatement cost:

$$G(e;\kappa,j) \equiv (1-\kappa)\, c_e\left(e+e^j,0\right) + \kappa c_e\left(e - \frac{(1-\kappa)\, e^j}{\kappa},1\right),\ j = t,n \ (\textit{trade, no trade}).$$

With trade at an interior equilibrium, the two types of firms have the same marginal benefits, p, so $G(e;\kappa,\text{ trade}) = p\,(e,\kappa)$. Without trade, the industry marginal benefit of emissions $G(e;\kappa,\text{ no trade})$ is a convex combination, with weights $1-\kappa$ and κ, of the marginal benefit for the two types of firms.

Investment lowers a firm's marginal abatement cost, but might increase or decrease the *slope* of marginal abatement cost. This fact is key to understanding why trade might increase equilibrium emissions. To emphasize this point, I express trade's effect on the relative magnitude of social marginal abatement cost, using information about the effect of investment on the slope of marginal abatement cost. To this end, begin with an arbitrary per firm allocation e, and consider a reallocation that gives s additional permits to each high cost firm ($K = 0$) and takes $\frac{(1-\kappa)}{\kappa}s$ permits from each low marginal cost ($K = 1$) firm. This reallocation holds fixed aggregate emissions. Of course, trade in permits results in a particular reallocation, i.e. a particular value of s. The following lemma provides the necessary and sufficient condition for this reallocation to *increase* the social marginal abatement cost.

Lemma 1 *A reallocation that transfers permits from low marginal abatement cost to high marginal abatement cost firms, holding fixed aggregate permits, increases industry marginal abatement cost if and only if*

$$\Delta\left(\kappa,e,s\right) \equiv \int_0^s \left(c_{ee}(e+y,0) - c_{ee}\left(e - \frac{(1-\kappa)\,y}{\kappa},1\right)\right) dy > 0. \tag{6}$$

The lemma states that if the marginal cost without investment is flat (i.e. the absolute value of the slope of marginal benefit of emissions is small), relative to the slope of the marginal cost with investment, then a reallocation of permits from low to high marginal cost firms, increases social marginal abatement costs. Lemma 1 implies:

Proposition 1 *Suppose* $0 < \kappa < 1$ *and Assumption 1 holds. A necessary and sufficient condition for permit trade to increase the equilibrium emissions level (leading to weaker environmental regulation) is that inequality (6) holds at* $e = e^{NT}$, $s = e^t\left(e^{NT};\kappa\right)$.

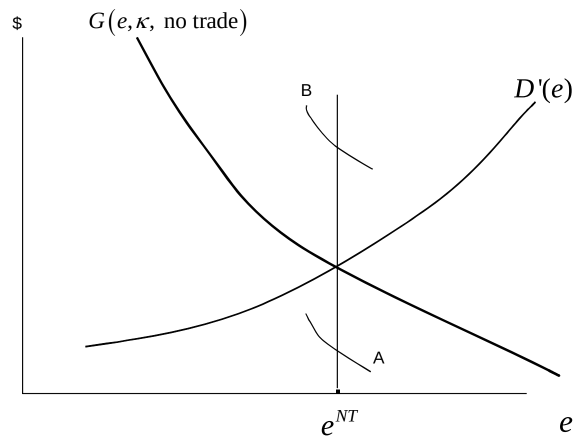

Figure 1: The marginal benefit of emissions without trade $G(e.\kappa, \text{ no trade})$ and the marginal damages, $D'(e)$. Curves A and B are fragments of possible marginal benefit curves with trade, $G(e.\kappa, \text{ trade})$

Proof. (sketch) Figure 1 shows the optimal level of emissions, absent trade, e^{NT}. The curves labelled A and B are fragments of two possible with-trade marginal benefit curves, $G(e, \kappa, \text{ trade})$; A lies below, and B above $G(e, \kappa, \text{ no trade})$ at $e = e^{NT}$. Denote e^T (T for trade) as the optimal level of emissions under trade, the unique (by Assumption 1) intersection of $G(e, \kappa, \text{ trade})$ and $D'(e)$. If $G(e, \kappa, \text{ trade})$ lies above $G(e, \kappa, \text{ no trade})$, as curve B, then Assumption 1 guarantees $e^T > e^{NT}$; reversal of the inequality implies that the planner's minimand is concave, violating Assumption 1. By Lemma 1, the condition given in the proposition is necessary and sufficient for $G\left(e^{NT}, \kappa, \text{ trade}\right) > G\left(e^{NT}, \kappa, \text{ no trade}\right)$. ■

Lemma 1 and Proposition 1 show that trade increases equilibrium emissions if the no-investment ($K = 0$) marginal abatement cost (equal to the marginal emissions benefit) is flat, relative to the with-investment ($K = 1$) marginal abatement cost, over the "appropriate interval". Figure 2 provides graphical intuition. Here I set $\kappa = 0.5$ and take as given the no-trade optimal level of emissions, e^{NT} (which depends on $D'(e)$). I also assume that if firms are allowed to trade, the equilibrium is interior, i.e. inequalities (4) are satisfied. As noted above, this assumption implies that $G(e; \kappa, \text{ trade}) = p(e, \kappa)$, the equilibrium permit price. Consequently, trade increases the equilibrium level of emissions if and only if the equilibrium permit price at $e = e^{NT}$ is above the convex combination of marginal costs for the two types of firms at $e = e^{NT}$.

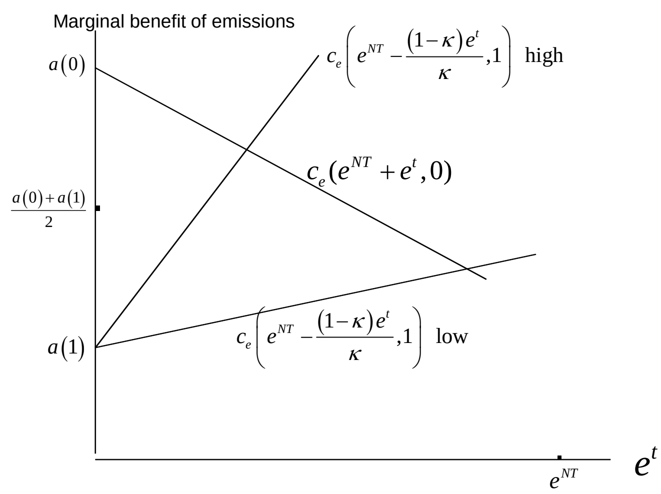

Figure 2: The curves labelled "high" and "low" correspond to two scenarios, with steep or flat marginal abatement for the firm that invested, relative to the firm that did not invest. The intersection of the positively and negatively sloped curves shows the equilibrium level of trade and the equilibrum permit price in the two scenarios.

The figure shows $c_e\left(e^{NT}+e^t,0\right)$, which decreases with trade, e^t, and two possible marginal cost curves, denoted "high" and "low", for firms that invested. Merely to keep the figure simple, these two cost curves have the same intercept, $a\left(1\right)$; for both curves, the equilibrium level of trade (equating marginal costs) is less than e^{NT}, so both equilibria are interior. Because $\kappa = 0.5$, $G\left(e^{NT},\kappa,\text{ no trade}\right) = 0.5\left(a\left(0\right)+a\left(1\right)\right)$. For the steep marginal cost curve ("high"), the equilibrium price exceeds $0.5\left(a\left(0\right)+a\left(1\right)\right)$, and the opposite holds under the relatively flat marginal cost curve ("low"). If investment leads to the "high" marginal cost curve, permit trade increases the equilibrium emissions level. If investment leads to the "low" marginal cost curve, permit trade reduces the equilibrium emissions level.

The area between the demand and supply curves in Figure 2 equals the trade-induced aggregate cost reduction, the gains from trade. The "low" cost scenario gains from trade are greater than the "high" scenario gains. The beginning of this section notes that trade has offsetting effects on the social marginal abatement cost (the marginal benefit of emissions). Trade lowers the cost of achieving any level of aggregate abatement, but trade also allocates an additional unit optimally across the firms, tending to increase the value of an additional unit of emissions (increasing social marginal abatement costs). Either of these effects might dominate. When the gains from trade are relatively small, as in the "high" cost scenario, the second effect is more likely to dominate, causing equilibrium emissions to be higher when firms can trade permits.[3]

4 The investment stage

When permits are not tradable, firms play a coordination game at the investment stage, creating multiple competitive investment equilibria and regulatory uncertainty. One of these competitive equilibria is constrained socially optimal. The constraint is the requirement that all firms emit at the same level. In contrast, the unique investment equilibrium under CAT is first best.

Firms in this model do not have the option to delay investment, e.g. until after the regulator announces the number of permits. Allowing costless delay reverses the timing of actions: regulation occurs before investment. In reality, both regulation and investment involve lags and adjustment costs; capturing these would require a multiperiod model.

4.1 Investment under command and control

Higher investment (larger κ) reduces the industry marginal abatement costs, lowering the equilibrium number of permits. As confirmation, differentiate the first order condition, equation (2) and use the second order condition, to obtain $\frac{de^{NT}}{d\kappa} < 0$. The representative firm takes κ as given and forms (point) expectations about this parameter; these expectations are correct in equilibrium. The firm's belief about κ (equal to its equilibrium value) affects its optimal investment decision. In the investment stage, a firm's net benefit of investing equals the difference between the costs when it does not invest, $-c(e(\kappa), 0)$, and the costs when it does invest, $-c(e(\kappa), 1)+\phi$. The benefit of investing, $\Pi^{NT}(\kappa)$, is therefore

$$\Pi^{NT}(\kappa) = c(e(\kappa), 1) - c(e(\kappa), 0) - \phi.$$

[3]Here is another perspective on the possibility that the two industry marginal abatement costs, under CAT and under command and control, might cross. For $0 < \kappa < 1$, define $\Theta(e; \kappa)$ as the difference: industry abatement costs under command and control minus industry abatement costs under CAT. For $e = e^{BAU}$ (the BAU level of emissions) abatement costs are zero with or without investment, so $\Theta(e; \kappa) = 0$. For $e < e^{BAU}$ it must be the case that $\Theta(e; \kappa) > 0$, because CAT reduces abatement costs. Thus, in the neighborhood of e^{BAU} it must be the case that $\Theta_e(e; \kappa) < 0$, i.e. industry marginal abatement costs are higher under command and control than under CAT. However, the fact that $\Theta(e; \kappa) > 0$ for $e < e^{BAU}$ does *not* imply that $\Theta(e; \kappa)$ is monotonic in e. At any extreme point, the industry marginal costs under CAT and under market based policies cross. If $\Theta(e; \kappa)$ is quasi-concave, then industry marginal costs are higher under CAT relative to command and control wherever $\Theta_e(e; \kappa) > 0$.

(NT again denotes "no trade".) Differentiating this expression and using $\frac{de^{NT}}{d\kappa} < 0$ implies

$$\frac{d\Pi^{NT}(\kappa)}{d\kappa} = \frac{(c_e^1 - c_e^0)^2}{S} > 0.$$

A larger anticipated value of κ increases the incentive to invest: the investment decisions are strategic complements.

The necessary and sufficient conditions for multiple equilibria are

$$\Pi^{NT}(0) = c(e(0), 1) - c(e(0), 0) - \phi < 0 \text{ and } \Pi^{NT}(1) = c(e(1), 1) - c(e(1), 0) - \phi > 0. \quad (7)$$

The first inequality implies that a firm does not want to invest if it knows that no other firm will invest ($\kappa = 0$); here the firm knows that the environmental standards will be lax. The second inequality implies that it pays a firm to invest if all other firms do so; here the firm knows that abatement standards will be strict. If both inequalities hold, there is an interior unstable equilibrium that satisfies $\Pi(\kappa_u) = 0$, where $0 < \kappa_u < 1$. At κ_u a firm is indifferent between investing and not investing. This equilibrium is unstable; for example, if slightly fewer than the equilibrium number of firms invest ($\kappa < \kappa_u$), it becomes optimal for all other investors to change their decisions, and decide not to invest. In summary,

Proposition 2 *Inequalities (7) are necessary and sufficient for the existence of two stable boundary equilibria (all firms or no firms invest) and one unstable interior equilibrium. If either inequality fails, there exists a unique boundary equilibrium.*

If ϕ is small, it is always optimal to invest; it is never optimal to invest if ϕ is large. Multiplicity requires moderate values of ϕ.

4.2 Investment under CAT

With trade, just as without trade, the regulator uses stricter environmental standards (smaller e) if more firms invest (larger κ). Totally differentiating equation (5), using the second order condition, implies $\frac{de}{d\kappa} < 0$. A Referees' appendix, available upon request, shows the derivations of non-obvious claims such as this one.

An increase in κ reduces the aggregate supply of permits (by making equilibrium regulation stricter), but also reduces the aggregate net demand for permits (by increasing the fraction of firms with low abatement costs). The effect of κ on the equilibrium price may therefore seem ambiguous. However, calculations establish $\frac{dp}{d\kappa} < 0$, and this inequality has a simple explanation. The equilibrium level of emissions is the same under CAT and an optimal emissions tax, and the equilibrium permit price equals the equilibrium tax. Because greater investment reduces the industry marginal cost of abatement, it must reduce the equilibrium tax – and the equilibrium permit price.

The total cost incurred by the investing firm, net of receipts from permit sales, and the cost incurred by the non-investing firm, including permit purchases, equal, respectively,

$$-c\left(e-\frac{1-\kappa}{\kappa}e^t,1\right)+\phi-p\frac{1-\kappa}{\kappa}e^t \quad \text{and} \quad -c(e+e^t,0)+pe^t.$$

The benefit of investing when firms can trade permits, $\Pi^T(\kappa)$, equals the difference between these two costs:

$$\Pi^T(\kappa)\equiv c\left(e-\frac{1-\kappa}{\kappa}e^t,1\right)-c(e+e^t,0)-\phi+p\frac{1}{\kappa}e^t.$$

Investment affects $\Pi^T(\kappa)$ via κ's effect on e, e^t, the ratio $\frac{1-\kappa}{\kappa}$, and finally on $p(\kappa)$. In view of the equilibrium conditions (3), the effect via each of the first three channels is 0, so κ affects $\Pi^T(\kappa)$ only via its effect on p. As a result:

$$\frac{d\Pi^T}{d\kappa}=\frac{e^t}{\kappa}\frac{dp}{dk}<0.$$

Under tradable permits, investments are strategic substitutes: an increase in the number of other investors decreases the incentive for any firm to invest. The monotonicity of $\Pi^T(\kappa)$ implies that for $0<\kappa<1$ there is at most one root of $\Pi^t(\kappa)=0$. In summary:[4]

Proposition 3 *When permits are tradable, investment decisions are strategic substitutes; there always exists a unique rational expectations competitive equilibrium. The equilibrium involves the fraction* $0<\kappa<1$ *of firms investing if and only if there is a solution to the equation* $\Pi^T(\kappa)=0$ *for* $0<\kappa<1$*. Therefore, an interior equilibrium exists if and only if*

$$\Pi^T(0)>0>\Pi^T(1).$$

If $\Pi^T(1)\geq 0$ *then the unique equilibrium is* $\kappa=1$*, and if* $\Pi^T(0)<0$ *then the unique equilibrium is* $\kappa=0$*.*

[4] The first part of Proposition 7 of Requate and Unold (2003) describes the outcome under tradable permits, in line with my Proposition 3. I include Proposition 3 so that the analysis here is self-contained, and in order to make the point that investment decisions are either strategic complements or substitutes, depending on whether the regulator uses command and control or cap and trade.

4.3 Trade's effect on the incentive to invest

Homogenous firms facing command and control emissions policies make the same investment decision. Therefore, firms remain homogenous ex post, so the prohibition against trade creates no apparent efficiency loss. In contrast, homogenous firms facing CAT make different investment decisions, are ex post heterogeneous and have gains from trade. The possibility of trade creates the rationale for trade. Command and control policies reinforce firm homogeneity. Section 5 relaxes the unnecessary and implausible simplifying assumption of ex ante homogenous firms.

Trade can either increase or decrease investment incentives. To verify this claim, and to understand when trade has one effect or the other, it is sufficient to consider cases where a set of measure 0 firms deviate from an extreme outcome where either $\kappa = 0$ or $\kappa = 1$. In both of these cases, the deviating firms benefit from trade, whereas the non-deviating firms do not, because each of the latter buys or sells an infinitesimal amount. Denote the gains from trade, received by the deviating firms, as a function of κ, as $GFT(\kappa) > 0$. If there is no trade and $\kappa = 0$, the deviating firms receive a (possibly negative) benefit of $\Pi^{NT}(0)$. With trade, the deviating firms receive this benefit, plus the gains from trade, so $\Pi^{T}(0) = \Pi^{NT}(0) + GFT(0)$; consequently, $\Pi^{T}(0) > \Pi^{NT}(0)$: if few firms invest, trade increases the incentive to invest. If there is no trade and $\kappa = 1$, the deviating firms receive the (possible negative) benefit of $-\Pi^{NT}(0)$. With trade, the deviating firms receive this benefit plus the gains from trade, so $-\Pi^{T}(1) = -\Pi^{NT}(1) + GFT(1)$; consequently, $\Pi^{T}(1) < \Pi^{NT}(1)$: if most firms invest, trade reduces the incentive to invest.[5]

These inequalities and the monotonicity of $\Pi^{T}(\kappa)$ and $\Pi^{NT}(\kappa)$ imply that the curves must cross a single time. Therefore, the investment equilibria with and without trade may differ considerably. For example, $\kappa = 1$ might be the unique with-trade equilibrium, while both $\kappa = 0$ and $\kappa = 1$ are equilibria without trade. There might be a unique interior equilibrium with trade, but two boundary equilibria without trade. The only impossible case is that there is a *different unique* boundary equilibrium with and without trade. For example, the case $\kappa = 1$ with trade and the unique equilibrium without trade is $\kappa = 0$ violates inequality $\Pi^{T}(1) < \Pi^{NT}(1)$.

[5] Firms here are risk neutral. Given the inability to costlessly delay investment, regulatory uncertainty has an ambiguous effect on risk averse firms' investment incentives. Informal evidence from the Portland cement market suggests that firms may have delayed investment while waiting for regulatory uncertainty to resolve. (Private communication, Meredith Fowlie.) See Fowlie, Reguant, and Ryan (2012) for empirical analysis of this industry.

4.4 Social optimality and emissions levels

CAT produces the social optimum regardless of whether the regulator distributes permits before or after firms invest, a familiar result.[6] Verification uses the fact that the optimality/equilibrium conditions are identical in the two with-trade scenarios, where the social planner chooses both κ and e, or chooses only e after firms choose κ.

The next result uses

Definition 1 *The second best (or constrained optimal) outcome is the socially optimal level of investment and emissions under the constraint that all firms receive the same number of non-tradable permits.*

Proposition 4 *(a) In the second best outcome, the planner instructs all or no firms to invest: $\kappa = 1$ or $\kappa = 0$ is constrained optimal. (b) The planner who chooses the emissions level before investment occurs, but does not directly choose investment, achieves the second best outcome. (c) When the regulator prohibits trade and announces the emissions ceiling after investment, one competitive equilibrium is second best.*

Permit trade can increase or decrease equilibrium emissions, for both fixed and endogenous investment, regardless of when the regulator issues permits. This claim relies on Proposition 1 and on the fact that trade has an ambiguous effect on equilibrium investment. Figure 3 illustrates the claim, showing equilibrium emissions as a function of investment costs, ϕ, for three scenarios. As κ ranges from 1 to 0 with increasing investment costs, emissions range from 0.4 to 0.5. The piece-wise linear curve shows equilibrium emissions with tradable permits. The heavy line segment covering $(0.104, 0.127)$ shows the range of investment costs producing two investment equilibria (where $\kappa = 0$ and $e = 0.5$ or $\kappa = 1$ and $e = 0.4$) when the regulator issues non-tradable permits after investment. This no-trade interval of multiplicity includes all costs producing an interior equilibrium with trade.

If the regulator distributes non-tradable permits *before* firms invest, Proposition 4 implies that equilibrium emissions is a step function (not shown). The vertical line at $\phi = 0.117$ shows the critical investment cost at which the step occurs For costs below (respectively, above) $\phi = 0.117$, the regulator announces $e = 0.4$ (respectively, $e = 0.5$)

[6] If the regulator announces an emissions tax before investment, the investment game has multiple equilibria (Proposition 6 in Requate and Unold (2003)). This result is fragile, relying on firms' assumed ex ante homogeneity. The ex ante optimal tax induces the unique first best equilibrium if there are even small differences across firms. Section 5.2 shows that, in contrast, the multiplicity of equilibria under command and control policies survives the introduction of a small amount of firm heterogeneity.

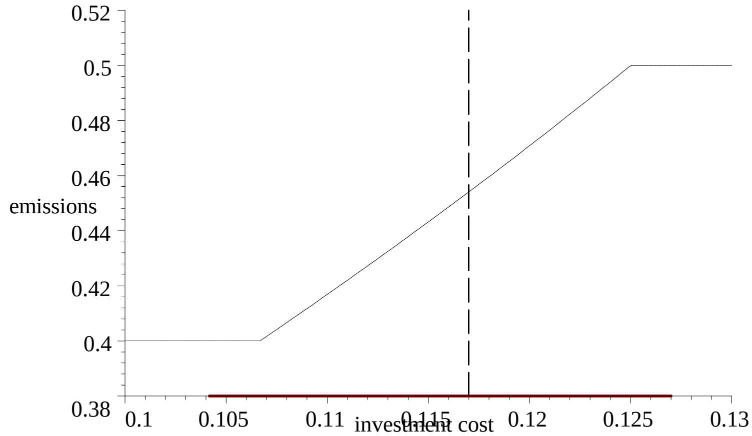

Figure 3: Effect of trade on equilibrium emissions, a function of ϕ, where $c_e(e, 0) = 1 - e$ and $c_e(e, 1) = 1 - 1.5e$ for $e < 0.66$, and $D'(e) = e$. Piecewise linear curve equals emissions under CAT. Heavy line on horizontal axis shows interval of indeterminacy under command and control, the interval $(0.104, 0.127)$. Social planner prefers $\kappa = 0$ outcome if and only if investment cost exceeds vertical line.

and all firms (respectively, no firms) invest. Under CAT the timing of the regulatory announcement is irrelevant. When the regulator announces a non-traded cap before investment, equilibrium emissions are lower than under CAT for low-intermediate costs $(.10667 \leq \phi \leq .117)$. For high-intermediate costs $(.117 < \phi \leq .125)$ emissions are lower with trade. This qualitative comparison holds in general; with trade, emissions are a continuous non-decreasing function of ϕ; with non-tradable emissions distributed before investment, emissions are a non-decreasing step function of ϕ. These two functions have the same domain and range, so they must cross. The figure also illustrates Proposition 4c: one equilibrium when the regulator distributes non-tradable permits after investment is constrained optimal.

5 Uncertainty and/or firm heterogeneity

Here I relax the assumption that firms face no uncertainty and are homogenous before they invest. This modification is interesting only in the command and control scenario, where actions are strategic complements.

Section 5.1, following Morris and Shin (2003), uses a "global game" to examine the situation where firms learn their different investment costs, or they receive different information about a parameter of the damage function. Previous global games applications include currency attacks (Morris and Shin 1998), bank runs (Goldstein and Pauzner 2005) and resale markets (Karp and Perloff 2005). In the deterministic (common knowledge) version of these games, agents' actions are strategic complements, leading to multiple equilibria. In the global game, firms receive private signals. Even if, after the signal, the uncertainty about the payoff-relevant variable is arbitrarily small, there is a unique equilibrium to the investment game; this is a familiar result in this literature. The new result is that this equilibrium is constrained socially optimal. The presence of public information may overturn uniqueness, thus overturning the constrained optimality.

Section 5.2 considers more conventional scenarios. For example, a firm's investment costs may be a draw from a distribution that is common knowledge. In this case, the results of the deterministic setting still hold if the support of the distribution is small; a unique equilibrium requires a large amount of firm heterogeneity, or equivalently a large amount of uncertainty. In another scenario, firms have common beliefs but are uncertain about whether the regulator will use CAT or command and control after investment.

5.1 Investment as a global game

Suppose firm i has investment cost $\phi_i = \bar{\phi} + \epsilon x_i$ where $\epsilon > 0$ and x_i is a mean zero random variable with known pdf $p(x)$. Firms do not know $\bar{\phi}$, but have diffuse priors (a uniform prior over the real line). A firm observes its private cost and then forms a posterior belief on $\bar{\phi}$. As ϵ approaches 0, firms know almost exactly average industry costs, and they know somewhat less precisely other firms' costs; higher order beliefs (the beliefs about what others believe about what others believe) become less certain, the higher the order of belief. Despite knowing average industry costs with high precision, firms remain uncertain about other firms' actions: even with arbitrarily small ϵ firms face considerable uncertainty about κ, inducing uncertainty about the second period emissions allowance. Due to this uncertainty, there is a unique equilibrium to the investment game.

Firms know that the non-tradable permit allocation will be $e^{NT}(\kappa)$, the solution to equation (2). The unique equilibrium to the investment game, a mapping from the signal ϕ_i to the action space: $\{$invest, do not invest$\}$, is independent of $p(x)$ and ϵ. This equilibrium survives iterated deletion of dominated strategies, and equals the optimal action for an agent who receives signal ϕ_i and believes that κ is uniformly distributed over $[0, 1]$. Without loss of generality, a firm indifferent between investing and not investing decides to invest.

Using Prop 2.1 in Morris and Shin (2003), a firm invests if and only if its signal ϕ_i

satisfies

$$\phi_i \leq \phi^c \equiv \int_0^1 \left(c(e^{NT}(\kappa), 1) - c(e^{NT}(\kappa), 0) \right) d\kappa \Longrightarrow \kappa^c \equiv \int_{-\infty}^{\frac{\phi^c - \bar{\phi}}{\epsilon}} p(x)\, dx, \tag{8}$$

where κ^c equals the equilibrium fraction of investors. I adopt

Assumption 2 $\phi^c \neq \bar{\phi}$,

which implies κ^c approaches 0 or 1 as $\epsilon \to 0$, depending on whether $\phi^c - \bar{\phi}$ is negative or positive. In the non-generic case $\phi^c = \bar{\phi}$, $0 < \kappa^c < 1$ for any ϵ.

Now consider the second best setting, where a regulator obtains a cost signal and then chooses κ and e to minimize its conditional expectation of $P(e, e, \kappa)$, defined in equation (1). The regulator's signal equals $\phi_r = \bar{\phi} + \epsilon_r x_r$ and x_r is a mean zero random variable with known density $p_r(x_r)$, so the regulator's conditional expectation of industry-wide average investment costs equals ϕ_r. Because P is linear in ϕ, the regulator's minimand equals the expression in equation (1), with ϕ_r replacing ϕ. The proof of Proposition 4 shows this function is concave in κ; therefore, the optimal investment decision, denoted κ^s, is always on the boundary. With the tie-breaking assumption that an indifferent planner chooses to invest, the planner sets $\kappa = 1$ if and only if

$$\phi_r \leq \phi^s \equiv c(e(1), 1) - c(e(0), 0) + D(e(0)) - D(e(1)). \tag{9}$$

Comparing the two thresholds establishes:

Proposition 5 *(a) The two thresholds are equal:* $\phi^c = \phi^s$. *(b) Under Assumption 2, the difference between the fractions of investors, and between the emissions levels, in the two scenarios (the global game and the constrained social outcome) approach zero as* $\epsilon \to 0$.

For small ϵ, the global games equilibrium is approximately (constrained) *socially* optimal. The global games equilibrium does not minimize the industry's expected costs. The industry as a whole would like to have all firms rather than no firms invest, given expected costs ϕ, if and only if

$$\phi \leq \phi^{cartel} \equiv c(e(1), 1) - c(e(0), 0). \tag{10}$$

Equations (9) and (10) establish $\phi^{cartel} < \phi^s$. The industry views the ex ante (before signal) expected equilibrium investment as excessive, but the constrained social planner considers it optimal.

Given the dearth of welfare results in global games, it is worth providing intuition for Proposition 5. The externality is associated with emissions, and only indirectly with investment. The competitive level of investment is socially optimal when the regulator corrects the emissions externality using CAT; here, the planner does not need a second policy instrument to target investment. In addition, non-tradable permits distributed before investment produces the constrained optimum emissions level. The competitive investment when the regulator distributes non-tradable permits after investment may not be constrained optimal, simply because it is not unique. The "problem", then, is the lack of uniqueness, not the presence of the constraint that firms receive equal non-tradable allocations. The lack of common knowledge in the global games setting "solves" the non-uniqueness problem, restoring constrained social optimality.

Example 1 *The marginal benefit of emissions without investment is* $c_e(e,0) = 1 - e$ *for* $e \leq 1$*; the marginal benefit with investment is* $c_e(e,1) = 1 - be$ *for* $e \leq \frac{1}{b}$*, where* $b > 1$*; and emissions damages are* $D(e) = \frac{\delta}{2}e^2$*, with* $\delta > b - 1$*. This inequality insures that for all* κ*, at the equilibrium level of emissions a firm that invests has a positive marginal benefit of emissions. The threshold investment cost in the global game and for the social planner is*

$$\phi^c = \phi^s = \frac{1}{2}\delta(b-1)\frac{b+\delta+1}{b(b+\delta)(\delta+1)}.$$

This function is increasing in both b *and* δ*. The location of the vertical line in Figure 3, identifying the discontinuity in the step function where* κ *jumps from 1 to 0, equals* ϕ^s*. A larger value of* b *increases the reduction in abatement cost due to investment. A larger value of* δ *decreases the equilibrium level of emissions for all* κ*. Either of these changes makes investment more attractive, increasing the threshold level of investment costs.*

Other global games settings The game above involves private investment costs, ϕ_i, but in other settings, agents may have private information about a parameter that affects all agents' payoffs. With the functions in Example 1, a firm's value of investing increases in δ, because a larger δ reduces the equilibrium emissions allowance. Suppose firms begin with diffuse priors over δ and then each receives a private signal δ_i. With minor changes in assumptions about the distribution of the signal, Proposition 2.2 of Morris and Shin (2003) now implies a threshold equilibrium value δ^c; firms invest if and only if $\delta_i \geq \delta^c$. The social planner's problem also has a threshold signal, δ^s. The parameter δ, unlike ϕ, affects the equilibrium emissions level, conditional on κ; δ enters nonlinearly the firm's and the social planner's payoffs obtained by replacing e with its equilibrium value. However, as ϵ approaches 0, the uncertainty with respect to δ is of no consequence in either problem. Only the strategic uncertainty about other agents' actions remains; this uncertainty produces the unique equilibrium in the global game setting. Thus, as ϵ approaches 0, the competitive equilibrium leads to the same outcome as the social planner's problem; that is, $\delta^c = \delta^s$.

The uniqueness result depends on the absence of public signals. With a public signal about ϕ (or about δ in the linear example), the competitive equilibrium need not be unique, and thus might not duplicate the constrained socially optimal equilibrium. With a public signal, uniqueness requires that the standard deviation of the private signal, as a ratio of the variance of the public signal, approach 0 (Hellwig 2002). The private signal must be sufficiently more precise than the public signal, for private information to induce uniqueness. For example, the public information embodied in interest rates likely restores multiplicity in the currency attack model, even when individual speculators have private information (Hellwig, Mukherji, and Tsyvinski 2006). There may be analogous considerations that restore multiplicity in the regulatory setting here.

5.2 Other types of uncertainty

Two alternatives to the global games model are worth considering. First, suppose that firm i's investment cost is a draw from the *known* distribution $p(\phi)$. Here, the firm's private information tells it nothing about the other firms' costs, because firms already know the distribution. Brock and Durlauf (2001) provide an example of such a game. As the support of $p(\phi)$ shrinks, firms become more similar, and the game approaches the deterministic game in the previous section. However, sufficient variability in the private cost produces a unique equilibrium.

As an illustration, let ϕ take two known values, ϕ_l and ϕ_h with equal probability, so the random variable has known mean $\bar{\phi}$. Suppose that in the deterministic game with $\phi = \bar{\phi}$ there are multiple equilibria. If, in the game with uncertainty, ϕ_l and ϕ_h are very close to $\bar{\phi}$, it is obvious that multiple equilibria remain. Here, a small amount of uncertainty (equivalently, a small amount of firm heterogeneity) does not induce a unique equilibrium. In contrast, if ϕ_l and ϕ_h are sufficiently far from $\bar{\phi}$ that they both lie in "dominance regions", then it is obvious that there is a unique equilibrium under uncertainty: firms use their dominant strategies. This example illustrates a situation where uniqueness requires a sufficiently large amount of uncertainty. In contrast, in the global games setting, an arbitrarily small amount of uncertainty yields uniqueness. (See however, the remark on public versus private signals above.)

For the second alternative, suppose firms expect to face CAT with probability p and to face command and control with probability $1-p$; this is the only source of uncertainty. For p close to 0 investment decisions are strategic complements as in section 4.1, and for p close to 1, actions are strategic substitutes as in section 4.2. At a critical level of p the nature of the game flips, and for higher values of p there is a unique equilibrium to the investment game, instead of multiple equilibria.

6 Conclusion

The fact that cap and trade pollution policies are more efficient than command and control policies is widely understood. However, the rationale for efficient policies is sometimes exaggerated, and a different reason to favor them is usually ignored. CAT – compared to command and control policies – might result in either more or less abatement, regardless of whether investment is fixed or endogenous, and regardless of whether the regulator announces the level of permits before or after firms invest. The fact that market based policies make abatement cheaper, does not imply that those policies lead to higher equilibrium abatement.

However, CAT reduces regulatory uncertainty. Under command and control policies, the lumpiness of investment and the fact that future environmental policies (optimally) depend on previous levels of investment, imply that there can be multiple rational expectations equilibria. From the standpoint of individual firms, this multiplicity looks like regulatory uncertainty. CAT eliminates this multiplicity of equilibria.

Because command and control policies create incentives for firms to make the same investment decision, these policies tend to reinforce firm homogeneity. This ex post similarity may make it appear that the prohibition against trade in permits is unimportant. In contrast, CAT encourages firms to make different investment decisions, thus creating or increasing firm heterogeneity, and increasing the efficiency gains from trade. The possibility of trade creates or increases the rationale for trade.

The potential regulatory uncertainty arises only when the regulator conditions the emissions ceiling on the previous aggregate investment, i.e. on the current industry abatement cost curve. If the regulator credibly commits to a level of non-tradable emissions before investment, there is obviously no regulatory uncertainty, and there is consequently a unique investment equilibrium. This competitive equilibrium involves all firms or no firms investing and is constrained optimal.

The potential regulatory uncertainty, when command and control policies are conditioned on past investment, depends on firms having common knowledge about market fundamentals. Even a small amount of private information about a market fundamental, such as average investment costs or the slope of marginal damages, leads to a unique equilibrium in the investment game. This equilibrium is constrained socially optimal: it reproduces the investment and abatement outcome selected by the regulator who distributes non-tradable permits before investment, or equivalently, the regulator who chooses both the investment and the abatement levels. Thus, in the global games setting (i.e. without common knowledge about market fundamentals) command and control policies create no regulatory uncertainty, leading to a constrained optimal level of investment and abatement. The introduction of public information may overturn this uniqueness, returning us to a world with multiple equilibria

These observations are interesting to the field of environmental economics, and regulatory economics more generally. They are of particular interest given the discussion of climate change policies occurring at all governmental levels. California's AB32 is a striking example. This law explicitly recognizes that future emissions levels will be conditioned on future contingencies. When ratified, it left open the possibility of using market based policies, without embracing those policies. There is still opposition to market based policies, so economists should be clear about what they do – and do not – achieve.

References

Biglaiser, G., J. Horowitz, and J. Quiggin (1995): "Dynamic pollution regulation," *Journal of Regulatory Economics*, 8, 33–44.

Brock, W., and S. Durlauf (2001): "Discrete choice with social interactions," *Review of Economic Studies*, 68, 235–260.

Carlsson, H., and E. Van Damme (1993): "Global Games and Equilibrium Selection," *Econometrica*, 61, 989–1018.

Economic and Technology Adancement and Advisory Committee (2008): "Draft Comments on the Draft Scoping Plan," http://arb.ca.gov/cc/etaac/meetings/090408pubmeet.

Fischer, C., I. Parry, and W. Pizer (2003): "Instrument choice for environmental protection when technological innovation is endogenous," *Journal of Environmental Economics and Management*, 45, 523–45.

Fowlie, M., M. Reguant, and S. Ryan (2012): "Market-based emissions regulation and industry dynamics," ARE Working Paper.

Gersbach, H., and A. Glazer (1999): "Markets and Regulatory Hold-up Problems," *Journal of Environmental Economics and Management*, 37, 151–164.

Goldstein, I., and A. Pauzner (2005): "Demand deposit contracts and the probability of bank runs," *Journal of Finance*, 39, 1293–1327.

Hellwig, C. (2002): "Public information, private information, and the multiplicity of equilibria in coordination games," *Journal of Economic Theory*, 107, 191–222.

Hellwig, C., A. Mukherji, and A. Tsyvinski (2006): "Self-fulfilling currency crises:the role of interest rates," *American Economic Review*, 96, 1769–1787.

Jaffe, A., R. Newell, and R. Stavins (2003): "Technological change and the environment," in *Handbook of Environmental Economics, volume 1*, ed. by K.-G. Maler, and J. Vincent, pp. 461–516. North-Holland, Amstredam.

Jaffe, A., and K. Palmer (1997): "Environmental regulation and innovation: a panel data study," *Review of Economics and Statistics*, 79, 610–619.

Karp, L., and J. Perloff (2005): "When promoters like scalpers," *Journal of Economic and Management Strategy*, 14, 447–508.

Karp, L., and J. Zhang (2012): "Taxes Versus Quantities for a Stock Pollutant with Endogenous Abatement Costs and Asymmetric Information," *Economic Theory*, 49, 371 – 409.

Kennedy, P., and B. Laplante (1999): "Environmental policy and time consistency: emission taxes and emission trading," in *Environmental Regulation and Market Power*, ed. by E. Petrakis, E. Sartzetakis, and A. Xepapadeas, pp. 116–144. Edward Elgar, Cheltenham.

Malueg, D. (1989): "Emission Credit Trading and the Incentive to Adopt New Pollution Abatement Technology," *Journal of Environmental Economics and Management*, 16, 52–57.

Milliman, S., and R. Prince (1989): "Firm incentives to promote technologicalchange in pollution control," *Journal of Environmental Economics and Management*, 17, 247–65.

Moledina, A., S. Polasky, J. Coggins, and C. Costello (2003): "Dynamic Environmental Policy with Strategic Firms: prices vs. quantities," *Journal of Environmental Economics and Management*, 45, 356 – 376.

Montero, J. (2002): "Permits, standards, and technology innovation," *Journal of Environmental Economics and Management*, 44, 23 – 44.

Morris, S., and H. Shin (1998): "Unique Equilibrium in a Model of Self-F lfilling Expectation," *American Economic Review*, 88, 587–597.

Morris, S., and H. Shin (2003): "Global Games: Theory and Applications," in *Advances in Economics and Econometrics*, ed. by M. Dewatripont, L. Hansen, and S. Turnovsky. Cambridge University Press.

Newell, R., A. Jaffe, and R. Stavins (1999): "The induced innovation hypothesis and energy- aving technological change," *Quarterly Journal of Economics*, 114, 941–75.

Popp, D. (2006): "International innovation and diffusion of air pollution control technologies," *Journal of Environmental Economics and Management*, 51, 46–71.

Requate, T. (1998): "Incentives to innovate under emissions taxes and tradeable permits," *European Journal of Political Economy*, 14, 139–65.

——— (2005): "Dynamic Incentives by Environmental Policy Instruments," *Ecological Economics*, 54, 175–195.

Requate, T., and W. Unold (2003): "Environmental Policy Incentives to adopt advanced abatement technology: Will the True Ranking Please Stand Up?," *European Economic Review*, 47, 125– 146.

Tarui, N., and S. Polasky (2005): "Environmental regulation with technology adoption, learning and strategic behavior," *Journal of Environmental Economics and Management*, 50, 447–67.

——— (2006): "Environmental regulation in a dynamic model with uncertainty and investment," Presented at NBER conference.

Taylor, M., E. Rubin, and D. Hounshell (2005): "Regulation as the mother of innovation: the case of SO2 Control," *Law and Policy*, 27, 348–78.

A Appendix: Proofs

Proof. (Lemma 1) Denote

$$\tilde{G}(e,s;\kappa) \equiv (1-\kappa)\, c_e\,(e+s,0) + \kappa c_e \left(e - \frac{(1-\kappa)\, s}{\kappa}, 1\right).$$

With this definition,

$$\tilde{G}(e,s;\kappa) - G(e;\kappa, \text{no trade}) = \int_0^s \frac{\partial \tilde{G}(e,y;\kappa)}{\partial y} dy = \Delta\,(\kappa, e, s)\,.$$

■

Propositions 2 and 3 summarize results shown in the text, so formal proofs are not shown.

Proof. (Proposition 4) Define $R\,(\kappa) = \min_e P\,(e,e,\kappa)$ where equation (1) defines $P\,(e,e,\kappa)$. Part (a) The assumption that investment reduces marginal abatement costs implies $c_e(e,0) - c_e(e,1) > 0$. The curvature assumptions imply $\frac{d^2P}{de^2} \equiv S > 0$, implying the comparative statics result $\frac{de^{NT}}{d\kappa} = -\frac{c_e(e,0)-c_e(e,1)}{S} < 0$. Using this inequality and the envelope theorem

$$\frac{d^2R}{d\kappa^2} = (c_e(e,0) - c_e(e,1))\, \frac{de}{d\kappa} < 0.$$

Therefore, the planner's minimization problem is concave in κ; the optimal κ is either 0 or 1.

Part (b). Consider the case where the constrained optimal level of investment is $\kappa = 1$. (The proof is similar when it is optimal to have $\kappa = 0$.) This assumption implies

$$-c(e\,(0)\,,0) + D(e\,(0)) - D(e\,(1)) > -c(e\,(1)\,,1) + \phi. \tag{11}$$

If the planner credibly announces $e^{NT}\,(1)$ at the investment stage, the individual firm does not care what other firms do. Suppose, contrary to the proposition, that a firm chooses not to invest. This hypothesis implies

$$-c(e\,(1)\,,1) + \phi > -c(e\,(1)\,,0). \tag{12}$$

Both inequalities (11) and (12) hold if and only if

$$D(e\,(0)) - c(e\,(0)\,,0) > D(e\,(1)) - c(e\,(1)\,,0). \tag{13}$$

Inequality (13) is false because by definition $e\,(0)$ minimizes social costs conditional on $\kappa = 0$.

Part (c) is trivial when there are two competitive equilibria, because these are both on the boundary, as is the second best outcome. Therefore, one of the competitive equilibria is not second best. The proof of part (b) establishes part (c) if there is a unique competitive equilibrium. ■

Proof. (Proposition 5) (a) Integrating the expression for ϕ^c in equation (8) by parts (using $e^{NT} = e\,(\kappa)$) gives

$$\begin{gathered}\phi^c = \int_0^1 \left(c(e(\kappa),1) - c(e(\kappa),0)\right) d\kappa = \\ \left(\left(c(e(\kappa),1) - c(e(\kappa),0)\right)\kappa\right)\big|_0^1 - \int_0^1 \kappa\left(c_e(e(\kappa),1) - c_e(e(\kappa),0)\right)\frac{de^{NT}}{d\kappa}d\kappa = \\ c(e(1),1) - c(e(1),0) - \int_0^1 \kappa\left(c_e(e(\kappa),1) - c_e(e(\kappa),0)\right)\frac{de^{NT}}{d\kappa}d\kappa.\end{gathered} \tag{14}$$

Define

$$g\,(\kappa) \equiv (1-\kappa)\,c_e\,(e\,(\kappa)\,,0) + \kappa c_e\,(e\,(\kappa)\,,1)\,.$$

Equation (2) states that $g\,(\kappa) = D'\,(e\,(\kappa))$. Use this relation and make a change of variables in equation (9), defining ϕ^s, to write

$$\begin{gathered}\phi^s = c(e\,(1)\,,1) - c(e(0),0) + D(e(0)) - D(e(1)) = \\ c(e\,(1)\,,1) - c(e(0),0) - \int_{e(0)}^{e(1)} D'\,(e)\,de = \\ c(e\,(1)\,,1) - c(e(0),0) - \int_0^1 D'\,(e)\,\frac{de^{NT}}{d\kappa}d\kappa = \\ c(e\,(1)\,,1) - c(e(0),0) - \int_0^1 g\,(\kappa)\,\frac{de^{NT}}{d\kappa}d\kappa.\end{gathered} \tag{15}$$

Using equations (14) and (15) gives

$$\phi^c - \phi^s =$$

$$c(e(1),1) - c(e(1),0) - \int_0^1 \kappa \left(c_e(e(\kappa),1) - c_e(e(\kappa),0)\right) \tfrac{de^{NT}}{d\kappa} d\kappa -$$

$$\left[c(e\left(1\right),1) - c(e(0),0) - \int_0^1 g\left(\kappa\right) \tfrac{de^{NT}}{d\kappa} d\kappa\right] =$$

$$c(e(0),0) - c(e(1),0) + \int_0^1 c_e\left(e\left(\kappa\right),0\right) \tfrac{de^{NT}}{d\kappa} d\kappa =$$

$$c(e(0),0) - c(e(1),0) + \int_{e(0)}^{e(1)} c_e\left(e\left(\kappa\right),0\right) de = 0.$$

(ii) This claim follows immediately from the fact that $\kappa^s \in \{0,1\}$, and that under Assumption 2 κ^c approaches either 0 or 1 as $\varepsilon \to 0$. In the non-generic case $\phi^c = \bar{\phi}$, for any $\epsilon > 0$ a non-negligible fraction of firms receive a signal above the threshold and a remaining fraction receive a signal below the threshold, so investment is bounded away from $\kappa = 0$ and $\kappa = 1$. The social planner always chooses $\kappa = 0$ or $\kappa = 1$. Therefore, the proposition requires Assumption 2. ■

B Referees' appendix: not intended for publication

The effect of k on the equilibrium level of emissions with trade): I begin by showing how κ affects the volume of trade for given e. Differentiating the first equation in the system (3) with respect to e^t and κ, holding e fixed, implies[7]

$$\frac{\partial e^t}{\partial \kappa} = \frac{c_{ee}^1}{\kappa c_{ee}^0 + (1-\kappa) c_{ee}^1} \left(\frac{e^t}{\kappa} \right) > 0. \tag{16}$$

If there are more adopters (larger κ) then each non-adopter buys more permits, holding fixed the aggregate supply of permits, e. I use the definition of $\Delta = \Delta(\kappa, e, e^t)$ from equation (6), fixing $s = e^t$. Differentiating the planner's first order condition, equation (5) implies

$$\begin{aligned} \frac{de}{d\kappa} &= \frac{(1-\kappa)\,\Delta \frac{\partial e^t}{\partial \kappa} - (c_e^0 - c_e^1) + \frac{e^t}{\kappa} c_{ee}^1}{S^t} \\ &= \frac{(1-\kappa)\,\Delta \frac{\partial e^t}{\partial \kappa} + \frac{e^t}{\kappa} c_{ee}^1}{S^t} \end{aligned}$$

The second equality uses the first equation in the system (3). Using equation (16) to eliminate $\frac{\partial e^t}{\partial \kappa}$ and simplifying produces

$$\frac{de}{d\kappa} = \frac{c_{ee}^0 c_{ee}^1}{\kappa S^t} \left(\frac{e^t}{\kappa c_{ee}^0 + (1-\kappa) c_{ee}^1} \right) < 0. \tag{17}$$

The effect of k on equilibrium purchases per non-adopter: I begin by totally differentiating the first equation in the system (3), again setting $s = e^t$ and using the definition of $\Delta(k, e, e^t)$ from equation (6), fixing $s = e^t$

$$\begin{aligned} \frac{de^t}{d\kappa} &= \frac{-\left(\Delta \frac{de}{d\kappa} - c_{ee}^1 \frac{e^t}{\kappa^2} \right)}{c_{ee}^0 + c_{ee}^1 \frac{1-\kappa}{\kappa}} \\ &= \frac{\left(-\Delta \frac{c_{ee}^0 c_{ee}^1}{\kappa S^t} \left(\frac{e^t}{\kappa c_{ee}^0 + (1-\kappa) c_{ee}^1} \right) + c_{ee}^1 \frac{e^t}{\kappa^2} \right)}{c_{ee}^0 + c_{ee}^1 \frac{1-\kappa}{\kappa}} \end{aligned}$$

[7] Recall the meaning of superscripts. These indicate that the function is evaluated at arguments corresponding to the type of firm (non-investor or investor). For example $c_{ee}^1 = c_{ee}\left(e - \frac{(1-\kappa)e^t}{\kappa}, 1\right)$.

The second equality uses equation (17). Simplifying produces

$$\frac{de^t}{d\kappa} = \frac{-\frac{\Delta}{S^t}\left(\frac{c^0_{ee}}{\kappa c^0_{ee}+(1-\kappa)c^1_{ee}}\right)+\frac{1}{\kappa}}{\kappa c^0_{ee}+(1-\kappa)\,c^1_{ee}} c^1_{ee}e^t. \tag{18}$$

The effect of investment on the equilibrium price of permits I begin with an intermediate result. Differentiating equation the first equation in system (3) (holding κ fixed) implies

$$\frac{de^t}{de} = -\frac{\kappa\Delta}{\kappa c^0_{ee}+(1-\kappa)\,c^1_{ee}}.$$

Substituting this result into the expression for $c^0_{ee}+S^t$ yields

$$\begin{gathered} c^0_{ee}+S^t = \\ c^0_{ee}+\left(-(1-\kappa)\,c^0_{ee}\left(1+\frac{de^t}{de}\right)-\kappa c^1_{ee}\left(1-\frac{1-\kappa}{\kappa}\frac{de^t}{de}\right)+D''\right) = \\ \kappa c^0_{ee}\left(1-\frac{1-\kappa}{\kappa}\frac{de^t}{de}\right)-\kappa c^1_{ee}\left(1-\frac{1-\kappa}{\kappa}\frac{de^t}{de}\right)+D'' = \\ \Delta\kappa\left(1-\frac{1-\kappa}{\kappa}\frac{de^t}{de}\right)+D'' = \\ \Delta\kappa\left(1+\frac{(1-\kappa)\Delta}{\kappa c^0_{ee}+(1-\kappa)c^1_{ee}}\right)+D'' = \\ \frac{\Delta\kappa c^0_{ee}}{\kappa c^0_{ee}+(1-\kappa)c^1_{ee}}+D'' \end{gathered} \tag{19}$$

With slight abuse of notation, write $p = p(\kappa) = p(e(\kappa),\kappa)$. Totally differentiating the second equation in system (3) and using equations (17), (18), and (19) implies

$$\begin{gathered} \frac{dp}{dk} = c^0_{ee}\left(\frac{de}{d\kappa}+\frac{de^t}{d\kappa}\right) = \\ c^0_{ee}\left(\frac{c^0_{ee}c^1_{ee}}{\kappa S^t}\left(\frac{e^t}{\kappa c^0_{ee}+(1-\kappa)c^1_{ee}}\right)+\frac{\left(\left(\frac{\Delta}{S^t}\left(\frac{c^0_{ee}}{\kappa c^0_{ee}+(1-\kappa)c^1_{ee}}\right)+\frac{1}{\kappa}\right)\right)}{(\kappa c^0_{ee}+(1-\kappa)c^1_{ee})}c^1_{ee}e^t\right) = \\ \frac{c^0_{ee}c^1_{ee}e^t}{S^t(\kappa c^0_{ee}+(1-\kappa)c^1_{ee})}\left(\frac{c^0_{ee}}{\kappa}+\left(-\Delta\left(\frac{c^0_{ee}}{\kappa c^0_{ee}+(1-\kappa)c^1_{ee}}\right)+\frac{S^t}{\kappa}\right)\right) = \\ \frac{c^0_{ee}c^1_{ee}e^t}{S^t(\kappa c^0_{ee}+(1-\kappa)c^1_{ee})}\left(\frac{c^0_{ee}+S^t}{\kappa}-\frac{\Delta c^0_{ee}}{\kappa c^0_{ee}+(1-\kappa)c^1_{ee}}\right) = \\ \frac{c^0_{ee}c^1_{ee}e^t}{S^t(\kappa c^0_{ee}+(1-\kappa)c^1_{ee})}\left(\frac{\Delta c^0_{ee}}{\kappa c^0_{ee}+(1-\kappa)c^1_{ee}}+\frac{D''}{\kappa}-\frac{\Delta c^0_{ee}}{\kappa c^0_{ee}+(1-\kappa)c^1_{ee}}\right) \\ \frac{c^0_{ee}c^1_{ee}e^t}{S^t(\kappa c^0_{ee}+(1-\kappa)c^1_{ee})\kappa}D'' < 0 \end{gathered} \tag{20}$$