Pollution Regulation of Competitive Markets

Krishnan S. Anand, François C. Giraud-Carrier

Abstract. We develop a model of oligopolistic firms that produce partially differentiated products and generate pollution as a byproduct. We analyze and compare two types of pollution regulation: Cap-and-Trade and Taxes. Firms can respond to regulation by any combination of pollution abatement, output reduction, emissions trading (under Cap-and-Trade), or payment of pollution taxes (under Taxes). We prove that well-chosen regulation can, besides reducing pollution, actually improve firms’ profits relative to laissez-faire (unregulated markets), and simultaneously improve consumer surplus and welfare. Thus, regulation Pareto-dominates laissez-faire under a wide range of plausible conditions. These results are driven by an unintended consequence of pollution regulation: Competing firms can use the regulation to tacitly (and credibly) collude to reduce production and improve their profits. We show that the degree of competition plays a critical role in determining the economic consequences of pollution regulation. Our results suggest that the regulator’s primary consideration should be the impact of regulation on consumers rather than producers.

1. Introduction

A firm’s pollution imposes a negative externality on society, in that pollution affects people, wildlife, and the natural environment outside of the firm’s boundaries. Hence, firms’ incentives to abate their pollution are not commensurate with the pollution damage they cause, rendering some regulation inevitable (see Pigou 1912). Nevertheless, opponents of pollution regulation, including industry groups and their lobbyists, claim that regulations choke businesses, hurt welfare, and destroy economic growth. For example, the U.S. Environmental Protection Agency (EPA) proposed national standards for airborne mercury pollution from coal-fired power plants in 2010. The National Association of Manufacturers objected vehemently to this proposal, stating that “overly burdensome and unnecessary rules . . . will crush economic growth and job creation” (Broder and Stolberg 2010). American Electric Power, one of the nation’s largest utilities, warned that “new air quality rules could force it to ‘prematurely’ shut down about two dozen big coal-fired units and fire hundreds of workers.” (New York Times 2011). Consumer advocates strongly supported the new EPA rule: Mercury is a deadly neurotoxicant that can permanently damage the brain and nervous system in fetuses and children. Dr. Marion Burton, President of the American Academy of Pediatrics, argued, “If you think it’s expensive to put a scrubber on a smokestack, you should see how much it costs to treat a child over a lifetime with a birth defect.” (Broder and Rudolf 2011). These arguments highlight the tension between two alternative approaches—output reduction and pollution abatement—to comply with pollution regulation. While producers were concerned about being forced to cut production, consumer advocates focused on pollution abatement as a way to protect the health of the population. Despite repeated legal challenges from industry groups, the EPA’s proposal went into effect and has been in place since 2015.

Do pollution regulations hurt producers, and to what extent? How do they affect consumers and welfare? How should firms respond to regulation, and what are the relevant strategic considerations for the pollution regulator? To address these questions, we develop an integrated production–pollution–abatement model, and study Cap-and-Trade and Pollution Taxes—two regulatory mechanisms extensively deployed in practice—under competition.

1.1. Competition in Polluting Industries

Canonical models that focus on either of two extremes—perfect competition or monopoly—neglect or downplay firms’ strategic interactions in the output markets: Perfect competition because each firm is a price taker with zero market power, and monopoly because
of the absence of competition. Demsetz (1981) is eloquent on the inadequacy of the perfect competition model. He argues that perfect competition is “...too static to reflect the essence of competitive activity” and characterized by “the complete absence of conscious control by anyone over the plans of others,” and hence, adds “only little to our understanding of competitive actions” [emphasis in the original]. In contrast to both perfect competition and monopoly, firms in our model are strategic competitors with market power; they respond to pollution regulation with some combination of pollution abatement, production adjustments (influencing prices and revenues in addition to pollution), trading in emission allowances, and payment of pollution taxes.

There is strong empirical evidence that polluting industries are dominated by a few competing firms holding significant market power. A few examples are provided below.

**Oil and Gas.** The oil and gas industry is the largest industrial source of smog, and also generates toxic air pollutants such as benzene, ethylbenzene, and n-hexane, linked to cancer and other serious diseases. Our analysis, based on data from the U.S. Energy Information Administration (U.S. Energy Information Administration 2018), shows that of 57 crude oil refining corporations in the United States, six control more than 50% of the total refining capacity, and 14 corporations control 80%.

**Cement.** Cement manufacturing accounts for about 5% of global human-generated CO₂ emissions, and also generates particulates (which are a mixture of fine solid particles and liquid droplets suspended in the air), nitrogen oxide, and sulfur oxide. Cement’s low profit-to-weight ratio makes transportation costly and favors local oligopolies (Drake et al. 2016a). The largest cement manufacturing company accounts for 19%, and the top five companies for 58.3%, of U.S. clinker capacity (Portland Cement Association 2016).

**Aluminum.** Aluminum production, which generates several toxic waste products such as particulates, fluorine compounds, alumina, carbon monoxide, carbon dioxide, and sulfur dioxide, is owned by just three companies in the United States, the largest of which (ALCOA) controls 52% of the market (Bray 2016).

1.2. **Summary of Contributions**

We prove that under oligopoly (and in contrast to monopoly), well-chosen Cap-and-Trade regulation can, besides reducing pollution, actually improve firms’ profits relative to laissez-faire (unregulated markets). It may also simultaneously improve consumer surplus, and hence welfare. As a result, well-chosen Cap-and-Trade regulation Pareto-dominates laissez-faire under a wide range of plausible conditions. These effects are driven by firms’ strategic trade-offs between output reduction and pollution abatement under competition. An unintended consequence of pollution regulation under competition is that it facilitates firms’ coordination: Firms are able to tacitly (and credibly) collude to reduce production—an irrelevant factor under monopoly or perfect competition. We show that the degree of competition plays a critical role in determining the economic consequences of pollution regulation. These results and their drivers have not been identified before in the literature. Collectively, our results suggest that the perceived risks to businesses from pollution regulation are perhaps exaggerated; the primary consideration should be its impact on consumers rather than producers.

We prove the equivalence of Cap-and-Trade and Taxes under oligopoly—a result previously established for the two extreme cases of perfect competition and monopoly. We prove equivalency in the following strong sense: Any Cap-and-Trade equilibrium can be mimicked under Taxes using the appropriate pollution tax rate, and any equilibrium under Taxes can be mimicked under Cap-and-Trade by capping total emissions appropriately. Moreover, the tax rate under Taxes is equal to the market-clearing price under Cap-and-Trade, which is also the equilibrium shadow price of firms’ pollution constraints. We show that, under Cap-and-Trade, *auctions and grandfathering* (free-of-charge initial allocations)—the two main alternative modes for allocating emission allowances—lead to identical equilibrium outcomes; this is an instantiation of the Coase Theorem.

A methodological contribution of our research is an integrated production–pollution–abatement platform for modeling pollution regulation, easily adapted for future research. Specifically, our model captures pollution generation, abatement levels and costs, and pollution damage. By parameterizing the degree of competition, our model captures a rich range of competitive markets, in which monopoly and Cournot oligopoly with undifferentiated products arise naturally as polar cases.

2. **Literature Review**

Research in sustainable operations has grown rapidly in recent years; the reader is referred to the excellent and comprehensive overviews by Kleindorfer et al. (2005), Corbett and Klassen (2006) and Souza (2012), as well as the compendium of recent research by Atasu (2016), and references cited therein. With environmental issues becoming paramount, Kleindorfer et al. (2005) propose that researchers “must revisit the classical models... [and] reformulate the objective function and the set of constraints.” In this spirit, our integrated production–pollution–abatement model...
overlays a classical model of competing producers with the important elements of pollution—including pollution generation, abatement, and damage—and its regulation.

Our model analyzes the effect of pollution regulation on industry profits, consumer surplus, and welfare. The extant literature has established that pollution regulation can improve firms’ profits under two alternative but technically restrictive assumptions: (i) profit overshifting (Seade 1985, Farzin 2003, Ehrhart et al. 2008, Christin et al. 2013) and (ii) salubrious demand-side effects of reduced pollution (Farzin 2003). Profit overshifting occurs when a firm’s profit increases under an adverse, exogenous cost shock. Seade (1985) identifies technical conditions on the elasticity of the slope of inverse demand that drive this unusual and counterintuitive phenomenon. The cost shock of Seade (1985) has been interpreted in follow-up environmental research as the firm’s cost of complying with pollution regulation. Following Seade (1985), Farzin (2003), and Christin et al. (2013) show that firms’ profits can improve with regulation. In Ehrhart et al. (2008), the elasticity of the cost-minimizing emissions function with respect to output plays an analogous role to the demand curvature of Seade (1985). They show that profits can increase in the emissions price. These technical conditions are very restrictive; Requate (2006) notes that such results “need an inverse demand function which has an extreme curvature.” Indeed, profit overshifting can never occur for the widely used linear demand curve (as we prove in Section 1 of the technical appendix). Additionally, Farzin (2003) assumes that reducing pollution increases industry demand, so that regulation improves firms’ profits even more. In contrast to this literature, we show that competing firms’ profits increase under pollution regulation, without either profit overshifting or the demand-side effects of Farzin (2003). In our model, competing firms can use the regulation to tacitly (and credibly) collude to reduce production and improve their profits.

We analyze and compare outcomes of Cap-and-Trade and Tax regulations under oligopolistic competition. In previous models establishing their equivalence, firms either did not compete in the output markets (under monopoly) or had zero market power (under perfect competition) (see Requate 2006); in many cases, even the emissions price was fixed exogenously. In effect, these models downplay firms’ strategic interactions in the output and emissions markets. In contrast, we model competition in both output and emissions markets, with all prices determined endogenously by firms’ strategies. Yet, as we show, Cap-and-Trade and Taxes are equivalent.

The literature identifies several conditions under which the equivalence between Cap-and-Trade and Taxes may break down, such as certain kinds of incomplete information (Weitzman 1974), divergent abilities to incentivize the adoption of pollution abatement technologies (Jaffe et al. 2003), stochastic emissions prices (Drake et al. 2016b, Islegen et al. 2016), and collusion in the emissions markets (Requate 1993b, 2006; Von der Fehr 1993; Ehrhart et al. 2008). In particular, our Cap-and-Trade model assumes that firms make emissions-trading and production decisions simultaneously, precluding collusion. Alternative timing assumptions leading to collusive outcomes are explored in the duopoly models of Requate (1993b), Von der Fehr (1993), Requate (2006), and Ehrhart et al. (2008). In these models, the two firms trade emissions in the first stage and decide on their production quantities in the second stage. In the first (trading) stage, the firms explicitly collude in order to maximize joint profits—that is, they jointly decide on their shares of permits and agree not to engage in further trade. Naturally, Taxes (which rule out collusion) and Cap-and-Trade (with overt collusion) cannot be compared. Moreover, such collusive agreements are forbidden by antitrust laws (Requate 2006).


3. Model

In this section, we develop our integrated production–pollution–abatement model, which combines a model of competing producers with a pollution model that includes pollution generation, abatement, and damage.

3.1. Modeling Competition

We consider $n \geq 2$ competing, profit-maximizing firms and study the strategic interactions among them and a pollution regulator. Firm $i$, for $i = 1, \ldots, n$, faces the linear inverse demand curve $p_i(q_i; Q_{-i}) = a - b \cdot q_i - \gamma \cdot b \cdot Q_{-i}$, where $q_i$ is the quantity produced by firm $i$, $Q_{-i}$ is the total quantity produced by all the other firms (firm $i$ excluded), $p_i$ is the resultant price, and $a > 0$, $b > 0$ and $0 \leq \gamma \leq 1$. Thus, firms compete à la Cournot. The linear downward-sloping demand curve has an appealing interpretation as the demand arising from the utility-maximizing behavior of consumers with...
quadratic, additively separable utility functions (Singh and Vives 1984). It has been used extensively in both theoretical and empirical literatures in economics, marketing, and operations management. Specific to our current study, another appealing feature of the linear demand curve is that it precludes profit-overshifting (as we prove), which would confound our results; recall the discussion in Section 2.

The parameter \( \gamma \in [0, 1] \) captures the degree of product substitution, and hence competition. The firms are monopolies when \( \gamma = 0 \), producing perfect substitutes when \( \gamma \in (0, 1) \) and perfect substitutes when \( \gamma = 1 \). It is clear that firms have market power and can influence prices through their production quantities \( \{q_i\}_{i=1}^n \). To focus on interesting cases, we assume that \( q_i > 0 \) \( \forall i \). (Setting \( q_i = 0 \) solves the pollution problem trivially.) Without loss of generality, the unit production costs are normalized to zero (see Christin et al. 2013). (Section 6 shows that all of our key results and insights hold under heterogenous production costs or market sizes.)

### 3.2. Modeling Pollution
Firms generate pollution as a byproduct of the production process. In turn, the pollution regulator enforces pollution controls on firms. Thus, while firms are profit-maximizers as in traditional supply chain research, they are further constrained by pollution regulations. Firms can respond to these constraints in several ways, including abating pollution at a cost and reducing production. Consider an arbitrary pollutant generated by the firms. The three important building blocks for a model of pollution—generation, abatement, and damage—are discussed below.

#### 3.2.1. Pollution Generation.
Let \( \bar{P}_i \) denote the pollution generated by firm \( i \) prior to any investment in abatement. Clearly, \( \bar{P}_i \) must be increasing in the production quantity \( q_i \). We assume that \( \bar{P}_i = e \cdot q_i \) where \( e > 0 \) is the emissions rate (see Requate 2006, Christin et al. 2013, Krass et al. 2013). A linear relationship between \( \bar{P}_i \) and \( q_i \) is a reasonable approximation in many industrial sectors—for example, when both pollution and production are linearly correlated to fuel consumption. Without loss of generality, we normalize \( e \) to 1—that is, \( \bar{P}_i = q_i \). (Section 6 shows that all our key results and insights hold under heterogenous emission rates.)

#### 3.2.2. Pollution Abatement.
Our model of pollution abatement relies on two complementary notions: (i) the abatement level, and (ii) the abatement cost. Firm \( i \) can control the pollution it emits by setting its abatement level \( x_i \in [0, 1] \), which is the percentage of pollution abated by the firm (see Krass et al. 2013). Thus, \( q_i \cdot x_i \) is the quantity of pollution abated, and the net (or residual) pollution \( P_i = q_i \cdot (1 - x_i) \). At one extreme, when \( x_i = 0 \), the pollution is unabated (hence, \( P_i = q_i \)). When \( x_i = 1 \), the pollution is completely abated and \( P_i = 0 \). More realistically, \( x_i = 1 \) corresponds to the situation wherein residual emissions are within the absorptive capacity of the natural environment, or the residual damage from that pollutant is insignificant. Intermediate values of \( x_i \) correspond to partial abatement.

The extant literature commonly assumes that pollution abatement costs are increasing and quadratic (see Subramanian et al. 2007), or at least convex increasing (see Nault 1996, Levi and Nault 2004) in the quantity of pollution abated, which is \( (q_i \cdot x_i) \) in our model. Hartman et al. (1997) study census data on common air pollutants—namely, particulates, sulfur oxides, nitrogen dioxide, carbon monoxide, hydrocarbons, lead, and other hazardous emissions—from 100,000 U.S. manufacturing firms across 37 industries. They find support for quadratic pollution abatement costs in several industries. Convex/quadratic abatement costs reflect the logic that the initial units of pollution are easy to abate, but once the low-hanging fruit have been exploited, pollution abatement becomes increasingly difficult. Thus, we assume that \( C_i(q_i; x_i) = c_i \cdot (q_i \cdot x_i)^2 \) \( \forall i \), where \( c_i \) is firm \( i \)'s abatement cost coefficient. (Section 6 shows that all our key results and insights hold under linear abatement costs—that is, when \( C_i(q_i; x_i) = c_i \cdot (q_i \cdot x_i) \).)

Abatement cost coefficients vary across pollutants, industries, geographic regions, and abatement technologies (Hartman et al. 1997, U.S. Census Bureau 2005, Creyts et al. 2007). Thus, we assume heterogeneous \( c_i \) in our model, and in the interests of analytical tractability, a binary support \( \{c_1, c_2\} \) for \( c_i \), where \( 0 \leq c_1 < c_2 \). Let \( m \) denote the number of low-cost firms; \( 0 \leq m \leq n \). It follows that there are \( (n - m) \) high-cost firms. We assume that \( n, m, c_1, \) and \( c_2 \) are common knowledge, but \( c_i \) is firm \( i \)'s private information, not known to the regulator or other firms. A standard informational assumption is that the regulator knows the available technologies and their prevalence, but not exactly which firm has which technology (Requate 2006). Thus, the regulator knows the distribution of abatement technologies in the industry, for which \( n \) and \( m \) are sufficient statistics.

#### 3.2.3. Pollution Damage.
Pollution affects human health, wildlife habitat, and the natural environment. In a widely cited study, Pope et al. (2002) found that a 10 \( \mu g/m^3 \) rise in particulate air pollution was associated with an increased mortality risk due to any cancer by 4%, cardiopulmonary cancer by 6%, and lung cancer by 8%. Particulates also contribute to the creation of haze, increase the acidity of lakes and rivers, and alter the balance of nutrients in waters and the soil (U.S. Environmental Protection Agency 2019). Sulfur dioxide, another common air pollutant, contributes to...
acid rains, which cause widespread damage to surface waters, aquatic animals, forests, crops, and buildings. We assume that the pollution damage can be quantified in monetary terms, as is common in the literature (see Atasu et al. 2009, Ata et al. 2012).

Convex pollution damage functions are a common assumption in the literature (see Nault 1996, Requate 2006, and the references therein). While pollution is tolerable in small quantities, “the marginal damage caused by a unit of pollution increases with the amount emitted” (Tietenberg and Lewis 2011). In fact, the EPA routinely uses convex (e.g., log-linear) functions to calculate the health impact of pollution (U.S. Environmental Protection Agency 2015). Thus, we assume that the pollution damage \( D(P) \) is increasing and convex in the total net pollution \( P = \sum_{i=1}^{n} P_i \). We let \( D(P) = d \cdot P^2 \), where \( d > 0 \), the pollution damage factor, is a measure of the toxicity of the pollutant. (Section 6 shows that all our key results and insights hold under linear pollution damage—that is, when \( D(P) = d \cdot P \).)

### 3.3. Performance Measures

Pollution regulation is contentious, since it affects multiple economic actors including firms and consumers in myriad, complex ways. Thus, performance measures are needed to help frame regulations that balance the interests of these diverse constituencies. These include output, firms’ profits, consumer surplus, and welfare—the last two augmented to include environmental effects. The consumer surplus (CS) is the difference between consumers’ willingness-to-pay and the price. A limitation of CS as a measure of consumers’ well-being is that it entirely excludes the effects of pollution damage on consumers. Hence, we define the augmented consumer surplus (ACS) as the consumer surplus net of the pollution damage; thus, \( ACS = CS - D(P) \). Let \( \Pi \) be the total profit across all firms. Then, welfare \( W = \Pi + ACS = \Pi + CS - D(P) \) (see Nault 1996, Levi and Nault 2004, Jacobs and Subramanian 2012, Krass et al. 2013). Our notations are summarized in Table 1.

### 4. Pollution Regulations

Centralized command-and-control mechanisms include technology mandates or performance standards, with heavy fines as a deterrent against violations. Often, centralized mandates are suboptimal because the regulator is usually ill-informed about each firm’s operating conditions, and efficiencies that could be achieved by tapping into firms’ expertise are forgone. To overcome these difficulties, economists have long urged the use of decentralized mechanisms relying on economic incentives—specifically, Cap-and-Trade and pollution taxes (Stavins 2003)—to accomplish pollution targets. We focus on these two popular mechanisms in this research.

### 4.1. Cap-and-Trade

Cap-and-Trade imposes a cap on the pollution emissions of a given pollutant, but firms can trade emission allowances with each other and thereby shift their individual pollution caps up or down. Cap-and-Trade is increasingly popular among environmental regulators. The U.S. Acid Rain Program of 1995 for sulfur dioxide emissions by coal-fired power plants is an early example; see Kros et al. (2012) for a fine overview. The European Union Emissions Trading System (2005), California’s Global Warming Solutions Act (2013), and China’s recent initiatives to control greenhouse gas emissions also deploy Cap-and-Trade.

Pollution regulators determine the cap by some combination of technological feasibility, cost–benefit analyses, and historical pollution levels. Let \( S \) denote the regulator’s target pollution cap over all the regulated firms. Assume without loss of generality that the initial allowances (prior to any trading) are \( \{s_i\}^{n}_{i=1} \), where \( s_i \) is the number of emission allowances available to firm \( i \), \( s_i \geq 0 \) for all \( i \), and \( \sum_{i=1}^{n} s_i = S \). For now, we are agnostic about the precise mechanism by which the regulator allocates allowances to individual firms. The initial allocation could be through auctions, grandfathering (free-of-charge initial allocations, which have been very popular; see Drake et al. 2016a), any combination of auctions and grandfathering, or any other mechanism.

We model the trading mechanism as part of the firms’ decision problem, from which the equilibrium
(market-clearing) price of emission allowances emerges endogenously. Let \( t_i \) be the number of emission allowances traded by firm \( i \). Without loss of generality, \( t_i \geq 0 \) indicates that firm \( i \) is a net seller of allowances, and \( t_i < 0 \) that the firm is a net buyer. Clearly \( t_i \leq s_i \), because the firm can only sell allowances up to its initial endowment. Let \( r \) denote the clearing price at which the emission allowances trade. Firm \( i \)'s problem is given by

\[
\max_{q_i>0,b\geq 0} \pi_i(q_i, x_i, t_i | Q_{-i}, r) = q_i \cdot p_i(q_i; Q_{-i}) - c_i \cdot (q_i \cdot x_i)^2 + r \cdot t_i
\]

subject to the pollution constraint

\[
q_i \cdot (1 - x_i) \leq s_i - t_i
\]

Any equilibrium must satisfy the market-clearing condition \( \sum_{i=1}^{n} t_i = 0 \). It is easy to see that firms must adhere to the pollution constraint by some combination of pollution abatement, output reduction, and trading. To eliminate distracting and uninteresting cases, we will assume in the rest of this paper that the industry cap \( S \in (0, \infty) \), where \( S = \frac{ma}{R(2 + (n-1)\gamma)} \) outside of this range, no trading occurs. To see why, first consider the firms' problem unconstrained by any pollution regulation. Since no firm will buy emission allowances, \( t_i \equiv 0 \forall i \). Thus, firm \( i \) chooses \( q_i \) and \( x_i \) to maximize its profit \( q_i \cdot (a - b \cdot q_i - \gamma \cdot b \cdot Q_{-i}) - c \cdot (q_i \cdot x_i)^2 \). The solution is \( x_i^* = 0, \; q_i^* = \frac{a}{b(2 + (n-1)\gamma)} \forall i \); firm \( i \)'s pollution is \( q_i^* \cdot (1 - x_i^*) = \frac{a}{b+2(n-1)\gamma} \) and the total pollution is \( S = \sum_{i=1}^{n} q_i^* \cdot (1 - x_i^*) = \frac{ma}{b(2 + (n-1)\gamma)} \). Thus, laissez-faire produces a pollution of \( S = \frac{ma}{b(2 + (n-1)\gamma)} \), and any cap \( S \geq \frac{ma}{b(2 + (n-1)\gamma)} \) is irrelevant. Now consider the case \( S = 0 \). This implies that \( s_i = t_i = 0 \). Hence, the firm’s pollution \( q_i \cdot (1 - x_i) = 0 \), and so \( x_i = 1 \forall i \), and the problem reduces to the well-known Cournot model with heterogeneous costs. Thus, the interesting, nontrivial cases where emissions trading can occur correspond to \( S \in (0, \infty) \).

Theorem 1 gives the unique Nash equilibrium under Cap-and-Trade. We let the subscripts \( l \) and \( h \) denote firms with low and high abatement costs, respectively, and superscripts \( ct \) and \( tax \) denote outcomes under Cap-and-Trade and Taxes.

**Theorem 1.**

i. A unique Nash equilibrium exists under Cap-and-Trade for any \( S \), any degree of competition \( \gamma \), and \( V \geq 0 \). The equilibrium is symmetric—that is, firms with identical abatement cost coefficients have identical production quantities and abatement levels. Further, we distinguish between two cases based on the tightness of the pollution cap. Specifically, there exists a threshold \( S \) such that:

Case 1, \( S > S \) (Moderate regulation; interior solution): \( q_i^c = q_i^f \) and \( 0 < x_i^c < x_i^f < 1 \). Further, \( \frac{\partial q_i^c}{\partial S} = \frac{\partial q_i^f}{\partial S} > 0 \).

Case 2, \( S \leq S \) (Stringent regulation; corner solution): \( q_i^c \leq q_i^f \) and \( 0 < x_i^c < x_i^f = 1 \). Further, \( \frac{\partial q_i^c}{\partial S} > 0 \), whereas \( \frac{\partial q_i^f}{\partial S} < 0 \), for \( \gamma > 0 \); \( \frac{\partial q_i^c}{\partial S} > 0 \), for \( \gamma = 0 \).

ii. Let \( \widehat{s}_i = s_i - t_i \) denote the posttrading emission allowances held by firm \( i \). The equilibrium solution \( \{q_i^c, q_i^f, x_i^c, x_i^f, r, \widehat{s}_i, \widehat{s}_h \} \) depends on the regulator’s total pollution cap \( S \), but is independent of the initial allocation \( \{s_i\}_{i=1}^{n} \), so long as \( \sum_{i=1}^{n} s_i = S \).

The results of Theorem 1 have important implications for the managers of firms facing pollution regulation. They highlight the importance of joint optimization of firms’ competitive and pollution abatement strategies. Moreover, the operational trade-offs between output reduction and pollution abatement play out differently depending on the stringency of pollution regulation. The equilibrium of Theorem 1 is illustrated in Figure 1, (a) and (b), for \( \gamma = 0 \) and \( \gamma > 0 \). First, consider Case 1 of Theorem 1 (moderate regulation), which leads to an interior solution. In the absence of trading, we would expect \( q_l > q_h \) due to the cost advantage of low-cost firms. Under Cap-and-Trade, however, both high-cost and low-cost firms produce identical quantities under moderate regulation (\( S > S \)). This is accomplished by low-cost firms selling emission allowances to high-cost firms. Thus, low-cost firms leverage their cost advantage through the selling of emission allowances rather than increasing production. Similarly, high-cost firms prefer to purchase permits from the low-cost firms, so that they can compete with the low-cost firms on equal terms in the output market. Thus, in the equilibrium under moderate regulation, low-cost firms abate more pollution than high-cost firms (i.e., \( x_l^f > x_h^f \)) for two reasons: (i) they have a cost advantage: \( c_l < c_h \); and (ii) the more they abate, the more emission allowances they can sell to high-cost firms.

Case 2 of Theorem 1 shows the effects of tightening the cap (\( S \leq S \)), leading to a corner solution: Under stringent regulation, low-cost firms move their abatement level to 100%—that is, \( x_l^f = 1 \). As a result, their production is no longer constrained by pollution regulation. High-cost firms cannot afford to set \( x_h^l = 1 \). Low-cost firms take advantage of stringent regulation, and the fact that \( x_l^f = 1 > x_h^f \), to (i) sell all their allowances to the high-cost firms (thus, \( \widehat{s}_i = 0 \)), and (ii) produce more than the high-cost firms (i.e., \( q_l > q_h \)). Furthermore, under competition (\( \gamma > 0 \)), low-cost firms take advantage of the tighter cap, and the inability of high-cost firms to respond, by increasing their production as \( S \) decreases (i.e., \( \frac{\partial q_i^c}{\partial S} < 0 \)), thus forcing high-cost firms to reduce production even more. Hence, in the region \( S \in (0, S) \), as \( S \) decreases, \( q_i^c \) falls (predictably), but \( q_i^f \) actually increases when \( \gamma > 0 \) (Figure 1(b)).
This last effect disappears under monopoly, where the competitive dynamics are absent, as can be readily seen when $\gamma = 0$. In this case, $q_i^t$ is constant in $S$ (Figure 1(a)).

Part (ii) of Theorem 1, that the equilibrium solution is independent of the initial allocation $\{s_i\}_{i=1}^n$, so long as $\sum_{i=1}^n s_i = S$, has an important implication: Any allocation rule—for example, auctions of all kinds, grandfathering or combinations of the two—would lead to the equilibrium of Theorem 1, and hence, the same consumer surplus and welfare. The result that equilibrium outcomes are robust to the initial allocation of allowances is an instantiation of the Coase theorem (Coase 1960).

Bovenberg et al. (2005) support grandfathering of initial allocations in the interests of political feasibility and to “insulate firms’ profits.” Indeed, grandfathering has been widely employed. It was used for 97% of allowances in the U.S. Acid Rain program (Kroes et al. 2012). Grandfathering also accounted for >95% of allowances in the first phase (2005–2008) and >90% in the second phase (2008–2012) of the European Union Emissions Trading System. In fact, although the European Union initially intended to auction all emission allowances in the third phase (after 2012), it switched back to grandfathering (Drake et al. 2016a). Under the Global Warming Solutions Act, the state of California uses grandfathering exclusively in electricity distribution and natural gas supply, and in sectors vulnerable to out-of-state competition (California Air Resources Board 2019). In the remainder of this paper, we will assume that emission allowances are grandfathered.

4.2. Taxes

Under Taxes, each firm pays a tax proportional to its emissions. Stavins (2003) documents the use of emission taxes on pollutants such as carbon monoxide, carbon dioxide, sulfur dioxide, and nitrogen oxides in Denmark, Finland, France, Italy, Netherlands, Norway, and Sweden. Carbon taxes are also used in Costa Rica, India, Ireland, Japan, South Africa, and Switzerland (Carbon Tax Center 2019). Recall that $S$ is the regulator’s aggregate pollution target. With this goal in mind, the regulator chooses a tax rate $\tau$. Each firm then chooses an output and an abatement level to maximize its profit net of the pollution tax. Firm $i$ pays a tax $\tau \cdot q_i \cdot (1-x_i)$, where $q_i \cdot (1-x_i)$ is its emissions. Thus, firm $i$’s problem is

$$\max_{q_i > 0, 0 \leq x_i \leq 1} \pi_i(q_i, x_i | Q_{-i}, \tau) = q_i \cdot p_i(q_i; Q_{-i}) - c_i \cdot (q_i \cdot x_i)^2 - \tau \cdot q_i \cdot (1-x_i).$$

We solve for the equilibrium under Taxes using backward induction. First, we solve for the firms’ Nash equilibrium in output and abatement levels as a function of $\tau$. Then, the regulator uses the equilibrium output and abatement levels to derive the minimum $\tau$ to ensure that $P = \sum_{i=1}^n P_i \leq S$. Theorem 2 derives the equilibrium under Taxes.

**Theorem 2.**

i. For any cap $S$, a unique Subgame-Perfect Nash equilibrium exists under Taxes, that is identical to the equilibrium under Cap-and-Trade. Thus, $\forall S, q_i^{tax} = q_i^{ct}$ and $x_i^{tax} = x_i^{ct}$, where $i \in \{1, h\}$. Further, the equilibrium tax rate $\tau(S)$ is unique and exactly equal to the Cap-and-Trade equilibrium (market-clearing) price $r(S)$.

ii. The total output, pollution damage, consumer surplus, augmented consumer surplus, and social welfare are all identical under Cap-and-Trade and Taxes.

iii. The one exception is firms’ profits: $\forall S, \forall i, \pi_i^{ct} - \pi_i^{tax} = \tau \cdot s_i > 0$. Thus, the difference in firms’ aggregate profits $\Pi^{ct} - \Pi^{tax} = \tau \cdot S$, the aggregate tax paid by firms under Taxes.
Theorem 2 proves that Taxes and Cap-and-Trade are equivalent under competition (i.e., for any $\gamma > 0$)—a result established previously for perfect competition and monopoly ($\gamma = 0$ in our model). To understand why $\tau = r$, observe that $r$ is equal to the Lagrangian multiplier of each firm’s pollution constraint under Cap-and-Trade (as shown in the proof of Theorem 1), which by definition is the shadow price of the pollution constraint—that is, the marginal cost of pollution abatement. In equilibrium, firms are indifferent between abating an additional unit of pollution and paying $r$ for the right to emit that extra unit. Under Taxes, in equilibrium, firms are indifferent between abating one more unit of pollution and paying an additional tax $\tau$. Hence, $\tau = r$. Both Cap-and-Trade and Taxes facilitate shifting the burden of pollution abatement from high-cost firms to low-cost firms, compensating them through revenues from the sale of surplus emission allowances or lower tax payments.

5. Policy Implications

In this Section, we study the impact of regulation on industry output, firms’ profits, consumer surplus, and welfare under varying degrees of competition ($\gamma$ varying from 0 to 1). We also study the impact of varying the proportion of low-cost firms. Although the equilibria, consumer surplus, and welfare are identical under Cap-and-Trade and Taxes, Cap-and-Trade with grandfathering leads to higher industry profits (Theorem 2). Thus, the regulator who cares about minimizing the adverse impact of regulation on firms (and fostering their cooperation) should use Cap-and-Trade with grandfathering. Hence, the rest of our analysis focuses on Cap-and-Trade.

5.1. Output

When the regulator wants to make the pollution target more stringent, she has to lower $S$. Recall that, in response to more stringent regulation, high-cost firms always decrease output, but low-cost firms may increase output under certain conditions (Case 2 of Theorem 1 with $\gamma > 0$, as illustrated in Figure 1(b)). Part (i) of Proposition 1 shows that aggregate output unambiguously decreases as the regulation becomes more stringent (i.e., as $S$ decreases) for any degree of competition $\gamma$, generalizing Requate’s results for monopoly (Requate 1993a) and Cournot oligopoly under Taxes (Requate 2006). Part (ii) of Proposition 1 analyzes the role of competition in driving the rate of output reduction in response to regulation.

Proposition 1.

i. For any $S$, any $\gamma \in [0, 1]$, and $\forall 0 \leq m \leq n$, the aggregate industry output strictly decreases as the regulation becomes more stringent. Formally, $\forall \gamma, S, m, n, \frac{\partial Q}{\partial S} < 0$.

ii. Competition mitigates the rate of output reduction in response to regulation. Formally, the cross-partial derivative $\frac{\partial^2 Q}{\partial S \partial \gamma} < 0$.

The pollution regulator wants to encourage pollution abatement and discourage output reduction, since lower output leads to higher prices and hurts consumer surplus and welfare. Part (i) of Proposition 1 shows that the regulator cannot forestall output reduction. Firms reduce output because in addition to helping them reduce pollution, the higher prices they are able to charge (due to their market power) partially compensates them for lower sales. In contrast, expenditures on pollution abatement have no such compensatory dynamic. As $\gamma$ increases, competition intensifies, which reduces firms’ market power. This limits firms’ ability to obtain higher prices by strategically reducing output; hence, $\frac{\partial Q}{\partial S}$ falls. To see this, observe that lowering $q_i$ unilaterally has a limited effect on $p(q_i; Q_{-i}) = a - b \cdot q_i - \gamma \cdot b \cdot Q_{-i}$, particularly when $\gamma$ is large, because competing firms would increase their output $Q_{-i}$, in response. This impels firm $i$ to favor pollution abatement over output reduction. Thus, an important implication of part (ii) of Proposition 1 is that increased competition helps align the firms’ incentives with the regulator’s goal of pollution abatement.

5.2. Industry Profits

Proposition 2 shows the critical role of competition in driving regulatory outcomes. In fact, although regulation hurts monopoly profits, moderate regulation improves the joint profits of competing firms relative to laissez-faire.

Proposition 2.

i. Under competition ($\gamma > 0$), there exists a range of moderate Cap-and-Trade regulation such that (a) industry profits strictly improve over laissez-faire (mathematically, $\exists S < S$ such that $\Pi_{\text{C}}^{(S, S)} > \Pi_{\text{C}}^{(S, S)}$, $\forall \gamma > 0$); and (b) industry profits strictly improve as, ceteris paribus, $c_i$ or $c_j$ increase, or as the number of low-cost firms $m$ decreases.

ii. Under monopoly ($\gamma = 0$), industry profits are strictly smaller under regulation than under laissez-faire. Mathematically, $\frac{\partial \Pi_{\text{C}}}{\partial S} > 0$, $\forall S < S$, when $\gamma = 0$.

Recall that $S \geq S$ corresponds to laissez-faire, in that the pollution cap does not constrain output (Section 4.1). Part (i.a) of Proposition 2 shows that by lowering the industry cap below $S$, firms’ profits under competition actually improve. This is because pollution regulation has two effects: a direct pollution-abatement effect and an indirect output-reduction effect (recall Proposition 1). Pollution abatement is costly and always lowers firms’ profits, but the effect of output...
reduction is ambiguous. We know that competition ($y \in (0,1)$) induces firms to overproduce relative to the profit-maximizing (monopoly) output. Collectively, firms would be better off if every firm lowered its output to keep prices high, but no firm is able to credibly commit to such a lower output. Unwittingly, pollution regulation provides such a coordinating mechanism: Since abatement is costly, firms can credibly use pollution constraints to tacitly collude to reduce output. The salubrious impact of output reduction on industry profits dominates the costs of pollution abatement under a range of moderate regulation, for all $y \in (0,1]$.

Part (i.b) of Proposition 2 sheds further light on the result of part (i.a). As either of the coefficients $c_l$ or $c_h$ increase, the pollution-abatement effect becomes stronger, which should dampen industry profits further. Simultaneously, however, the output-reduction effect is also amplified, since firms can credibly commit to even lower output levels. Part (i.b) of Proposition 2 shows that the latter effect dominates; hence, industry profits strictly increase in both $c_l$ and $c_h$. A similar effect—due to an increase in firms’ aggregate abatement costs—is observed as the number of low-cost firms $m$ decreases. Our results suggest that paradoxically, Cap-and-Trade regulation is particularly beneficial to firms in industries characterized by high abatement costs, or in which there are few firms with efficient abatement technologies. Indeed, a cross-industry EPA study shows that some of the most polluting and highly concentrated industries—oil and gas, cement and aluminum (recall Section 1.1)—also have among the highest pollution abatement costs as a percentage of value of shipments: 1.14% for primary metals (e.g., aluminum), 0.79% for oil and gas, and 0.61% for nonmetallic minerals (e.g., cement). Across all industrial sectors, these percentages ranged from 0.08% to 1.14% with a mean of 0.44% (U.S. Census Bureau 2005).

Part (ii) of Proposition 2 follows because under unregulated monopoly ($y = 0$), each firm has optimized its output for its market, and further output reduction (induced by regulation) can only hurt revenues and profits. Thus, both pollution-abatement and output-reduction effects work in the same direction and hurt monopoly profits.

Proposition 2 can also be understood through the lens of externalities. The important difference in pollution regulation of competing firms (versus a monopoly or perfect competition) is the presence of a “competitive externality” in addition to the pollution externality. Competing firms are trapped in an equilibrium where each firm’s decisions (e.g., production and abatement) impose not just a pollution externality on society but also a competitive externality on the other firms. For example, a competitor unilaterally raising its output reduces other firms’ profits because of the competitive externality. Therefore, under competition, pollution regulation indirectly limits output, thus mitigating both pollution and competitive externalities. Proposition 2 proves that under moderate Cap-and-Trade regulation, the benefits to firms from limiting the competitive externality (i.e., through output reduction) outweigh their abatement costs in equilibrium. Of course, this would not happen in a monopoly, because there is no competitive externality. Hence, any regulation is detrimental to the monopoly list. (Under perfect competition also, the competitive externality is irrelevant because firms make zero profits under either laissez-faire or regulation.)

To summarize, the conventional wisdom that regulation would hurt firms’ profits holds only for monopolies. As we proved, the degree of competition is paramount in determining whether firms’ profits are hurt by pollution regulation. Recall the example cited in our opening paragraph, of American Electric Power’s threat to shut down several power plants and fire hundreds of workers in response to new EPA regulations. The same article states, “This is a deceptive and particularly cynical claim. The utility is making a business decision that has little to do with the rules.” The units proposed to be shut down were 55 years old on average, with many already scheduled for retirement and some operating at only 5% of capacity (New York Times 2011). Perhaps such reflexive resistance to any pollution regulation is misplaced.

5.2.1. Impact of Emissions Trading. To understand the impact of emissions trading, we compare Cap-and-Trade with the pure Cap mechanism that does not allow trading (proofs are available from the authors on request). We focus on moderate regulation (the interior solution of Theorem 1). As discussed above, heterogeneous firms use emissions trading to tacitly collude, leading to lower total output than laissez-faire. However, as Figure 2(a) illustrates, the output under Cap-and-Trade is higher than that of Cap. Emissions trading shifts some of the burden of pollution abatement from high- to low-cost firms, which lowers the industry’s abatement costs, inter alia leading to higher aggregate output (and higher industry profits).

Moreover, for any pollution target $S_t$, emissions trading maximizes production efficiencies by equalizing marginal revenues across firms. This leads to $q^{cl}_t = q^{cl}_h$ in our model, because output markets are symmetric (Figure 2(b)). Firms with low abatement costs are compensated for lowering their output by selling emission allowances to high-cost firms, which are then able to increase their output. Figure 2(b) also illustrates that, in the Cap equilibrium, the marginal revenues from the output markets are not equalized across low and high abatement cost firms, which we know is inefficient. (Even under heterogeneous markets,
modeled in Section 6, we can show that marginal revenues across firms are equalized in the Cap-and-Trade equilibrium, although generally, $q_i^{ct} \neq q_h^{ct}$.

Finally, emissions trading also leads to abatement efficiencies by equalizing marginal abatement costs across firms. Without trading, the equilibrium is inefficient, leading to different marginal abatement costs (see Figure 2(c)).

To summarize, emissions trading facilitates tacit collusion among heterogeneous firms on total output and also enables both production and abatement efficiencies.

5.3. Welfare

It is clear that consumer surplus (CS) always falls with regulation, due to output reduction (recall Proposition 1). However, the effect of regulation on Augmented Consumer Surplus (ACS)—the consumer surplus net of the pollution damage—is ambiguous because regulation also mitigates pollution damage. Additionally, regulation affects firms’ profits (recall Proposition 2), which compounds the effect on welfare. Proposition 3 shows that the pollution damage factor $d$ and the degree of competition $\gamma$ together determine the desirability of regulation; moderate regulation improves both ACS and welfare (over laissez-faire) for a wide range of values of $d$ and $\gamma$.

**Proposition 3.**

i. Under well-chosen moderate regulation, the augmented consumer surplus is strictly greater than under laissez-faire, when $d > D_\gamma \equiv \frac{b_{clch}}{2n_{clch} + (2 + (n - 1)\gamma)\theta(n(n - m)k + m\zeta)}$. Mathematically, $\exists S < \bar{S}$ such that $ACS_{S < S} > ACS_{S \geq \bar{S}}$, $\forall \gamma$ and $d > D_\gamma$.

   ii. Under well-chosen moderate regulation, welfare is strictly greater than under laissez-faire, when $d > d_\gamma \equiv \frac{b_{clch}(1 - (n - 1)\gamma)}{2n_{clch} + (2 + (n - 1)\gamma)\theta(n(n - m)k + m\zeta)}$. Mathematically, $\exists S < \bar{S}$ such that $W_{S \leq \bar{S}} > W_{S \geq \bar{S}}$, $\forall \gamma$ and $d > d_\gamma$.

   When $\gamma \geq \frac{1}{n - 1}$, $d_\gamma \leq 0$, leading to Corollary 1.

**Corollary 1.**

i. Moderate regulation improves welfare for all $d$ when $\gamma \geq \frac{1}{n - 1}$, or equivalently, when $n \geq 1 + \frac{1}{\gamma}$.

   ii. Moderate regulation improves ACS and welfare for all $\gamma$ when $d > d_0 = \frac{b_{clch}}{2n_{clch} + (n(n - m)k + m\zeta)}$. Thus, moderate regulation is Pareto-improving for all $\gamma$ when $d > d_0$.

Proposition 3 and Corollary 1 show that regulation can improve welfare over laissez-faire over a wide range of parameter values, particularly when competition is intense ($\gamma > \frac{1}{n - 1}$), the number of competing firms is large ($n > 1 + \frac{1}{\gamma}$) or the pollutant is sufficiently harmful ($d > d_\gamma$).

Figure 3 illustrates Proposition 3 and Corollary 1. Moderate regulation strictly improves industry profits when $\gamma > 0$ (by Proposition 2), which enhances welfare; hence, $D_\gamma \geq d_\gamma$. In fact, regulation improves welfare for a wide range of parameters (as also suggested by Corollary 1). Intuitively, for a pollutant with high $d$ (i.e., $> D_\gamma$), moderate regulation improves both ACS and welfare, because the reduction in pollution...
damage dominates the economic losses from output reduction (region R1 of Figure 3). In combination with Proposition 2, regulation is Pareto improving over laissez-faire in region R1—that is, both producers and consumers are better off, even as the regulator meets her pollution target. In the intermediate region R2 ($d_0 < d \leq D_0$), the economic losses to consumers from output reduction dominate the reduction in pollution damage; hence consumers are worse off, and ACS goes down. However, firms are better off from output reduction, and the overall effect in region R2 is that regulation improves welfare. When $d$ is small (i.e., $d < d_0$; region R3), the pollutant’s harmful effects are so mild that the economic losses from output reduction dominate the reduction in pollution damage. Regulation worsens both ACS and welfare in region R3, and laissez-faire is the optimal policy. In the special case of monopoly ($\gamma = 0$), regulation hurts welfare for all $d < d_0$. As Figure 3 illustrates, pollution regulation is more likely to improve consumer surplus and welfare under competition ($\gamma > 0$) than under monopoly ($\gamma = 0$).

To summarize, firms’ profits increase under moderate regulation relative to laissez-faire for any $\gamma > 0$. However, regulation hurts consumers in the entire region ($R2 + R3$). These observations suggest that, contrary to firms’ concerns, the paramount factor in framing pollution regulations should be its effect on consumers rather than on producers.

Finally, part (ii) of Corollary 1 shows that when $d \geq d_0$, regulation improves ACS and welfare for any degree of competition (i.e., any $\gamma \geq 0$), and also increases industry profits under Cap-and-Trade. Note that $d_0$ is increasing in $c_\gamma$, and $\lim_{\gamma \to 0} d_0 = 0$. Thus, for low $c_\gamma$, regulation is beneficial even for mild pollutants (i.e., those with small pollution damage factors), since region R3 of Figure 3 shrinks as $d_0$ falls. This result is true for any $m > 0$, suggesting that the benefits of even isolated innovations in abatement technologies (for example, those relating to green technologies) would diffuse through the complex interplay among firms’ production and abatement strategies, potentially benefitting all firms and consumers. Over time, as technologies scale up and improve, one would expect the cost of pollution abatement to go down, making the case for pollution regulation even more compelling.

5.4. Varying the Proportion of Low-Cost Firms

This section analyzes the effects of varying the number of low-abatement cost firms $m$, while keeping the total number of firms $n$ and other parameters constant.

Proposition 4.

i. Increasing the number of low-abatement cost firms mitigates the rate of output reduction in response to regulation. Formally, the cross-partial derivative $\frac{\partial Q}{\partial m} - \frac{\partial Q}{\partial fi} < 0$.

ii. As $m$ increases,

a. the region where regulation is Pareto-improving expands. (This is Region R1 in Figure 3.) Formally, $D_\gamma$ is decreasing in $m$.

b. The region where regulation improves welfare expands. (This is Region R1 + R2 in Figure 3.) Formally, $d_\gamma$ is decreasing in $m$.

c. The region where regulation is Pareto-improving for any $\gamma$ expands. (This is the region $d \geq d_0$ in Figure 3.) Formally, $d_0$ is decreasing in $m$.

iii. As $m$ increases, the feasible region for an interior solution under regulation expands; correspondingly, the region with the corner solution shrinks. As $m$ approaches $n$, the corner solution entirely disappears. Formally, $S_{cl}$ (recall Theorem 1) is decreasing in $m$, and as $m \to n$, $\frac{S_{cl}}{S} \to 0$.

The results of Proposition 4 are once again driven by the strategic trade-offs between pollution abatement and output reduction, mediated this time by $m$. As $m$ increases, the industry’s costs of pollution abatement falls. Hence, firms respond to regulation by abating more pollution, and resorting less to output reduction, at any pollution cap $S$. This explains part (i) of the proposition. Further, higher pollution abatement and smaller output reduction improve consumer surplus, which explains part (ii). As $m$ increases, the burden of pollution abatement is shared by a larger number of low-cost firms, thereby making the corner solution of maximum abatement by any individual firm less likely. This leads to part (iii) of Proposition 4. The result of part (iii) is appealing not just because consumer surplus becomes less likely, but also because
corner solutions arise under harsh pollution regulations ($S \leq S$), which are politically contentious (Bovenberg et al. 2005).

6. Alternative Model Specifications
We saw that moderate Cap-and-Trade regulation improves competing firms’ profits relative to laissez-faire; consumer surplus and welfare simultaneously improve under plausible conditions. The equilibria under Cap-and-Trade and Taxes are identical, and the Cap-and-Trade equilibrium depends only on the total number of allowances, and not on individual allocations. We study the robustness of these results by analyzing a number of alternative model specifications. We model heterogeneous production costs, market sizes, and emission rates in lieu of heterogeneous abatement costs. We also study linear (instead of convex) abatement costs and pollution damage.

We prove that all the above results hold under each of these alternative specifications (proofs are available with the authors). In all variants, the results mimic the pattern in Figure 3 (i.e., $\exists D, d$, such that $S$). Moderate Cap-and-Trade regulation always improves welfare if $\gamma > \frac{1}{1+\gamma}$, as in the main model. Our results show that Cap-and-Trade is a robust mechanism that improves firms’ coordination and performance through emissions trading under all kinds of heterogeneity. As discussed in Section 5.2.1, Cap-and-Trade facilitates interfirm efficiencies for both production and abatement.

7. Summing Up: Managerial Insights and Future Directions
Several years ago, research in supply chain management exploded in response to the increasing importance of *interfirm* operational issues. This research integrated interfirm coordination, information, and agency issues within traditional operations research. Similarly, as we have argued, the study of environmental policy needs to expand the scope of traditional supply chain management to include environmental considerations, which are becoming increasingly important for business (recall Kleindorfer et al. 2005). Our research shows that competition, and the ensuing strategic interactions among firms, are paramount considerations in determining regulatory goals and outcomes, and that Cap-and-Trade can improve firm profits, consumer surplus, and welfare, even while effectively meeting regulatory goals.

7.1. Managerial Implications
For the individual firm, the operational trade-offs between output reduction and pollution abatement play out differently depending on abatement costs. We saw that firms with low abatement costs leverage their cost advantage through abating more pollution and thereby selling more emission allowances to their competitors, even if this increases competitors’ production at the expense of their own. Firms with an abatement cost disadvantage employ the reverse strategy: They purchase permits from their low-cost competitors in order to compete effectively in the output market. Thus, by cleverly harmonizing their output, abatement costs, and emissions trading, all firms are better off. Under Cap-and-Trade, managers with access to more efficient abatement technologies gain a competitive advantage not just in the output markets, but also by selling emission allowances—including to competitors. In fact, managers can amplify their competitive advantage from different kinds of assets, such as production technologies with lower costs or lower emissions, through emissions trading.

Rather than reflexively opposing pollution regulation, managers in competitive industries should embrace moderate Cap-and-Trade regulation, especially with grandfathering; after all, as we proved, industry is made better off by regulation under any degree of competition. Emissions trading helps firms in several ways. It facilitates tacit collusion, and also enables production and abatement efficiencies, all of which can improve a firm’s profits even relative to laissez-faire. Managers’ receptiveness to newly proposed pollution regulations must take cognizance of their competitive environment, which is a critical driver of regulatory outcomes.

7.2. Directions for Future Research
Our integrated production–pollution–abatement model contributes several building blocks—notably of pollution generation, abatement, damage, and regulation—that can serve as a foundation for future research on pollution regulation under more elaborate supply chain or production structures. Our model assumed that pollution is observable, contractible, and a deterministic function of production quantities. The resulting pollution damage was also deterministic and common knowledge. We ignored informational frictions such as monitoring and auditing costs, so that the regulator could verify compliance or levy taxes costlessly. Future research could relax each of these assumptions, and study optimal policy under unobservable or stochastic emissions and damage, and related informational frictions. Assuming stochastic pollution damage is appropriate particularly in the case of accidents leading to hazardous emissions, which requires the regulator to hold firms liable for negligence (Serpa and Krishnan 2016). The study of liability regulation in the context of competitive markets should be an interesting question for future research. Another potentially interesting research area
is the impact of asymmetric information relating to production or abatement costs. These relaxations lead to interesting agency problems.

Our model assumed that firms compete on quantities. Quantity competition is a natural assumption to model the production–pollution–abatement dynamic, since pollution levels and abatement costs are both functions of production quantities. An interesting direction for future research would be to extend our model to price competition in the output market.

We have argued that the pollution regulator should take competition (and firms’ market power) into account in designing effective regulation that balances the interests of all constituencies. In fact, even this may only be the first step. As Requate (2006) notes, “Strictly speaking, the regulator has to know the whole vertical structure [supply chain], including the degree of market power at each step of the production chain, in order to determine the optimal tax rate [or emission caps].” As researchers in operations, we would add to this the question of which echelons in the supply chain should be regulated for optimal regulatory outcomes (Caro et al. 2013). There has also been some recent research on related contexts including end-of-life product recovery mandates (Jacobs and Subramanian 2012) and apportioning of emission costs among coproducts (Sunar and Plambeck 2016).

The optimal regulation of a supply chain wherein firms at different echelons vary in their market power is a potentially exciting area for future research where operations researchers are well positioned to contribute.

Acknowledgments
The authors are indebted to the department editor (Vishal Gaur), the anonymous associate editor, and three anonymous reviewers for their many valuable suggestions. They are very grateful to Manu Goyal of the University of Utah for his insightful comments.

References
http://www.carbontax.org/services/where-carbon-is-taxed/.

Anand and Giraud-Carrier: Pollution Regulation of Competitive Markets


