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Allocating Emissions Among Co-Products: Implications for Procurement and Climate Policy

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Co-production (simultaneous production of multiple outputs) occurs in some emission-intensive basic material and agricultural industries. This paper is motivated by ones in which a supplier sells its primary product to a buyer that incurs an emissions cost (voluntarily, or due to government-imposed climate policy) and sells co-products into markets without emissions costs. Emission-accounting standards provide three candidate rules for allocating the supplier's emissions among its products. This paper shows that under the value-based allocation, imposing an emissions tax on the primary product can increase emissions, by motivating the supplier to lower the price and sell a larger quantity. In contrast, with the socially optimal choice of allocation rule characterized in this paper, imposing the emissions tax on the primary product can greatly reduce emissions and increase welfare. In the absence of climate policy, under value-based allocation, a buyer might achieve greater profit by paying to offset its supply chain emissions. That can motivate supplier innovation to reduce its production cost. In numerical examples, considering the rare earth cerium oxide (co-produced with iron) and palm oil (co-produced with palm meal), the choice of allocation rule has a large impact on emissions, a buyer's profit, and social welfare.

Keywords: greenhouse gas emissions; allocation; supply chain; voluntary offsetting; border adjustment
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1. Introduction

This paper provides guidance for buying firms, environmental nongovernmental organizations (NGOs), and climate policy makers grappling with the following questions: For a process that simultaneously produces multiple types of output (co-products), how should the process greenhouse gas emissions be allocated among the co-products? Should a region with climate policy impose an emissions tax on imports? Should a buying firm commit to reduce or offset its supply chain greenhouse gas emissions? This paper examines how an emissions tax on imports (or, equivalently, a buyer's voluntary commitment to reduce or offset its supply chain emissions) affects a co-product supplier's pricing, a buyer's order quantity, and the resulting greenhouse gas emissions, buyer profit, and social welfare, under the candidate rules for co-product emission allocation.

In greenhouse gas emission accounting, co-product emission allocation is an important issue, for three reasons. First, roughly half of all anthropogenic greenhouse gas emissions may be attributed to the production of food and basic materials.[1] Second, the production of food and basic materials commonly generates co-products (Chen et al. 2013, Boyabatlı 2015), and co-production is increasingly prevalent in emission-intensive agricultural, steel, and chemical industries wherein firms are converting process waste into a co-product (Lee 2012, Boyabatlı 2015). Third, some specific products with co-products—palm oil, for example—have immense associated emissions. Indonesia is the world's third largest emitter of greenhouse gases (behind China and the United States) primarily due to its emissions associated with palm oil production (*Forbes* 2014, World Resources Institute 2015).

The issue of co-product emission allocation is contentious in the context of voluntary greenhouse gas emission accounting. At present, the standards for greenhouse gas emission accounting (the GHG Protocol, ISO 14041, and PAS 2050) allow for process emissions to be allocated in proportion to the economic *value* of a co-product, in proportion to the *mass* of a

[1] Food production accounts for a quarter of anthropogenic greenhouse gas emissions (Vermeulen et al. 2012). Production of basic materials (metals, chemicals, minerals, paper, petroleum products) accounts for between 23% and 30% of all anthropogenic emissions, based on (Herzog 2009). Industrial emissions (in large part, the emissions caused by energy generation for industrial use) amount to 32% of all anthropogenic greenhouse gas emissions (Intergovernmental Panel on Climate Change 2014), and production of basic materials accounts for approximately 85% of all industrial energy use (Intergovernmental Panel on Climate Change 2007).

co-product, or based on a system *expansion*. The latter accounts for avoided emissions from other sources that would produce a market substitute for a co-product. However, observers complain that a buying firm can understate its supply chain emissions by choosing the allocation rule that assigns the minimum emissions to an input; observers and some buying firms want to eliminate the flexibility to choose the allocation rule (World Resources Institute 2011). Despite engagement by NGOs, Walmart, PepsiCo, and other prominent buyers (World Resources Institute 2011, Brown et al. 2010), this issue remains unresolved.

The issue of co-product emission allocation is crucial and unresolved also in the context of international trade and climate policy. A quarter of global CO_2 emissions from fossil fuels occur in production of goods for export (Davis and Caldeira 2010). (That estimate assumes a value-based allocation of emissions from industrial sectors from which one co-product is consumed domestically and another co-product is exported.) Therefore, as documented in Condon and Ignaciuk (2013), policy makers in the European Union (EU) and other regions with climate policy are contemplating "border adjustment." Border adjustment would apply an emissions tax (or requirement to purchase emissions permits within a cap-and-trade system) to goods imported from a region without climate policy. Specifically, under World Trade Organization (WTO) law, a border adjustment must apply the same tax (or permit price) per unit emissions that is in effect in the importing region with climate policy. The crucial unresolved issue is how to assign an amount of emissions to an imported product. To facilitate implementation, governments are likely to apply border adjustments only to emission-intensive basic material and agricultural products (Condon and Ignaciuk 2013), some of which have co-products, so the question of how to allocate process emissions among co-products must be resolved.

This paper analyzes a model in which an emission-intensive supplier exports its "primary" product to a region with climate policy (or buyer with voluntary emissions-related commitment), sets the price for its primary product, and sells one or more co-products locally at exogenous prices. The model is motivated by the following examples, drawn from the supply chains of Walmart, General Motors (GM), Interface, and PepsiCo. First, the Chinese company Inner Mongolia Baotou mines cerium oxide and iron ore, which naturally occur together in fixed proportions. Baotou exports cerium oxide to the European Union and United States, wherein it has nearly 90% market share and hence pricing power, and sells the iron ore in China at the prevailing market price (Stanway and Hopfner 2011, Tse 2011). Cerium oxide is an essential input to the windows and catalytic converters of GM's automobiles and the glass screens in consumer electronics sold by Walmart (Credit Suisse 2011, Hocquard 2010, Kirby 1997). Second, Mexico's oil monopoly PEMEX refines petroleum into naptha and gasoline. It exports naphtha to the United States, wherein it is the dominant supplier of naphtha and can set its price, and sells gasoline in Mexico at a price set by Mexico's government (U.S. Energy Information Administration 2011, Buchanan 2011). Naphtha is transformed into the nylon fiber in Interface's carpet and various polymers in GM's automobiles and Walmart's plastic consumer products (European Commission 2004, BASF 2006, Kallman 2009). Third, in Brazil, Citrovita-Citrosuco grows oranges and processes them into juice and pulp. It is the dominant supplier of orange juice to the European Union (and supplier to PepsiCo Tropicana) and sells the pulp for animal feed locally at the market price (Martens and Kassai 2011, Neves 2008).

The buyers in those three examples have made voluntary commitments that, in effect, impose a cost per unit emissions. Interface has made a commitment to offset the supply chain emissions for its "cool carpet," so its cost per unit emissions is the cost of an offset credit (Interface 2013). Walmart has committed to reduce its supply chain emissions (Plambeck and Denend 2010). According to the CDP (2013), many companies with a target for emissions reduction, including Walmart, use the shadow price as the cost per unit emissions to incentivize and coordinate employees to meet the target. Whereas Interface and Walmart have made commitments regarding their supply chain emissions, PepsiCo and GM have made commitments regarding only their direct or downstream emissions (PepsiCo 2012, General Motors 2011).

1.1. Preview of Results

Section 3 develops three "counterintuitive" results. An emissions tax on imports can increase emissions and a buyer's profit. Increasing the tax per unit emissions also can do so. Requiring a buyer to use the maximum of the candidate allocations (thereby maximizing the emissions tax per unit product) can increase emissions and the buyer's profit, relative to the status quo in which the buyer chooses the allocation rule. The driver of all three results is that by reducing the price for its primary product, a supplier with co-products reduces the value-based allocation of emissions to its primary product, which reduces the buyer's emissions cost per unit product and thus increases the buyer's order quantity.

Then, for a buyer, §3.1 characterizes the profit-maximizing allocation rule and conditions under which the buyer can achieve greater profit by starting to incur a cost in proportion to its supply chain emissions.

For a policy maker, §3.2 characterizes the allocation rule that minimizes emissions and shows that, under realistic conditions, implementing an emissions tax on imports with that allocation rule maximizes social welfare for the region with climate policy.

For a supplier, §3.3 shows that an emissions tax on imports (or equivalently, a voluntary commitment by a buyer to reduce or offset its supply chain emissions) can justify investment in process improvement to reduce the unit production cost, but only under value-based allocation or through improvements (e.g., in energy efficiency) that simultaneously reduce the emission intensity of production.

Whereas the base model formulation has a monopolist supplier, §3.4 explains how all the results extend to a setting with competition among multiple suppliers.

Sections 4.1 and 4.2 parameterize the model to represent the U.S. flat glass industry (which imports cerium oxide) and the EU margarine industry (which imports palm oil). In both numerical examples, the choice of allocation rule has a large impact on emissions, buyers' profits, and social welfare. In the cerium oxide numerical example, §4.1 shows that the aforementioned "counterintuitive" results occur at plausible levels of the tax per unit emissions.

1.2. Related Literature

Our paper bridges three distinct bodies of literature: the climate policy literature on border adjustment, the managerial literature on why firms should voluntarily mitigate their greenhouse gas emissions, and the operations management (OM) literature on co-production. The former two do not yet focus on the "operational" detail of co-production, and the latter does not yet focus on greenhouse gas emissions or strategic (game theoretic) buyer–supplier interactions.

An extensive policy literature, surveyed in Fischer and Fox (2012) and Condon and Ignaciuk (2013), examines the impact of border adjustment on international trade and greenhouse gas emissions, but without studying the issue of co-product emission allocation. Most of that literature employs computable general equilibrium (CGE) models. Some of the CGE papers implicitly assume a mass-based allocation of process emissions among co-products (for example, see Babiker and Rutherford 2005), and others implicitly assume a value-based allocation (for example, see Weisbach et al. 2013), but the CGE papers do not discuss the issue of how to allocate process emissions among co-products and implications thereof. Other border adjustment papers restrict attention to a single industry with a single product, to deal with the complexity of imperfect competition. In those single-industry-imperfect-competition papers and ours, a cap-and-trade system is equivalent to an emissions tax, because firms in the industry are assumed to be price takers in the market for emissions permits, which spans many industries (Fowlie et al. 2016). Two of the single-industry-imperfect-competition papers are not in the aforementioned surveys: Fowlie et al. (2016) empirically estimates a model of how cement manufacturers dynamically adjust their capacities and choose production quantities over time. In Drake (2015), oligopolistic manufacturers choose their emission intensity, production quantities, and whether or not to incur a fixed cost to shift production to a region without climate policy. In Fowlie et al. (2016), Drake (2015), and all the papers surveyed in Fischer and Fox (2012) and Condon and Ignaciuk (2013), imposing a border adjustment emissions tax on imports reduces emissions, relative to the base case with only a domestic tax on emissions, and increasing the magnitude of the tax per unit emissions further reduces emissions (recall that the border adjustment tax per unit emissions must be the same as in the domestic economy, under WTO law). Our paper is the first to model co-product emission allocation and imperfect competition, which together give rise to the contradictory result that imposing a border adjustment or increasing the magnitude of the tax per unit emissions can increase emissions.

A managerial literature describes various sorts of benefits that a firm might gain by making a voluntary commitment to mitigate its greenhouse gas emissions, including influence over future climate change regulation, enhanced corporate reputation, access to capital, employee motivation, retention and recruitment, and increased market share (Lyon and Maxwell 2003, Hoffman 2005, Plambeck 2012, Finster and Hernke 2014). For example, according to Peters-Stanley and Yin (2013), Interface has gained marketing advantage from its commitment to offset its supply chain emissions. This paper identifies a different benefit not previously described in the literature: price reduction by a co-product supplier.

An extensive literature, surveyed in Chen et al. (2013), Boyabatlı (2015), and Bansal and Transchel (2014), addresses operations management for a co-product manufacturer. Most of those papers assume that the co-products are vertically differentiated by quality level. Under that assumption, Chen et al. (2013) and Tomlin and Wang (2008) examine how the co-product manufacturer should set prices. In Devalkar et al. (2011), Boyabatlı (2015), Boyabatli et al. (2015), Lee (2012), in the initial stage of production in Dong et al. (2014), and in our paper, the manufacturer produces horizontally differentiated co-products in a fixed ratio of quantities; according to Chen et al. (2013), Boyabatlı (2015), such papers are surprisingly scarce given the prevalence of that phenomenon in practice. Lee (2012) describes how steel and chemicals manufacturers are innovating to convert process waste into a saleable co-product and, for a monopolist manufacturer, identifies conditions under which that innovation leads to a higher optimal production quantity and hence potentially higher environmental impact. Lee (2012) also analyzes an innovation-licensing game between duopoly manufacturers; in contrast, all the other OM co-product literature examines *single*-firm decision problems with correspondingly richer operational details. To the best of our knowledge, our paper is the first to analyze a strategic (game theoretic) supply chain interaction between a co-product manufacturer and buyer, and the first in the OM co-production literature to focus on greenhouse gas emissions.

Several OM papers address greenhouse gas emission taxes but not co-production. A small tax on emissions can greatly reduce emissions by motivating a large change in the economic order quantity (Chen et al. 2013). In contrast, a plausibly small emissions tax has little effect on retail facility location (Cachon 2014) or freight transport mode (Hoen et al. 2014). Increasing the emissions tax can deter a manufacturer from improving the energy efficiency or emission intensity of production (Krass et al. 2013, Plambeck and Taylor 2013). Taxing a manufacturer's direct emissions can backfire by causing the manufacturer to make operational decisions that increase its overall supply chain emissions (Benjaafar and Chen 2014). In the nascent literature on supply chain emission accounting, Caro et al. (2013) model the efforts of multiple firms in a supply chain to reduce their joint emissions and show that "overallocation" (the emissions allocated to each firm summing to more than the total supply chain emissions) is necessary to induce the optimal emission-reduction efforts. Granot et al. (2014) advocate a Shapley value rule that allocates supply chain emissions fully, without overallocation, and has a value-based allocation of process emissions among co-products. Jira and Toffel (2013) identify various factors associated with a supplier's willingness to disclose information about its emissions, using data from the Carbon Disclosure Project.

The economics literature establishes that a standard sales tax (fixed percentage of the selling price) yields higher welfare than a fixed tax per unit product; see Katrak (1977), Keen (1998), and papers surveyed therein. The rationale is that the standard sales tax motivates a supplier to lower its price to lower the tax per unit product. Value-based allocation also does so. However, in contrast to the aforementioned economics literature, this paper shows that under realistic constraints and specified conditions, welfare is maximized with an allocation rule that does *not* vary with the supplier's price.

2. Model

There are $N \geq 1$ firms in a region with climate policy, and these firms buy product A from a supplier located in a region without climate policy. The supplier sets the price p_A per unit of product A. Then, each buyer $n \in \{1, \ldots, N\}$ chooses its order quantity q_n for product A. The supplier produces to fill the buyers' orders, incurring cost k_s and generating emissions e_s per unit production. Buyer n incurs operating cost k_b per unit and generates emissions e_b per unit from its own operations associated with the transportation, transformation, and retailing of product A. Buyer n incurs emissions cost $t(e_b + \gamma)$ per unit order quantity, where $t > 0$ is the cost per unit emissions in the region with climate policy (t may be an emissions tax, as in Japan, or the permit price for emissions under a cap-and-trade system, as in the European Union). If the region with climate policy does not impose a border adjustment, then $\gamma = 0$; otherwise, under border adjustment, γ represents the amount of emissions assigned to a unit of product A. Finally, buyer n sells quantity q_n at price $r(\sum_{n=1}^{N} q_n)$, where $r(\cdot)$ denotes the buyers' inverse demand function.

Whereas product A is the supplier's primary product, to produce one unit of A, the supplier also produces one unit of each of $N_C \geq 1$ different co-products. The supplier sells each of its co-products $c \in \{1, \ldots, N_C\}$ locally, at exogenous price $p_c > 0$ per unit. By supplying a unit of c to the market, the supplier reduces emissions from other sources by e_c. Typically, e_c represents the emissions from production of the market substitute for a unit of co-product c.

This paper follows the Greenhouse Gas Protocol, ISO 14041, and PAS 2050 standards in assuming that emissions must be assigned to product A according to value-based allocation

$$\gamma_V = e_s \frac{p_A}{p_A + \sum_{c=1}^{N_C} p_c}, \tag{1}$$

mass-based allocation

$$\gamma_M = e_s \frac{\beta_A}{\beta_A + \sum_{c=1}^{N_C} \beta_c}, \tag{2}$$

where β_A and β_c denote the mass of one unit of product A and of co-product c, respectively, or according to system expansion

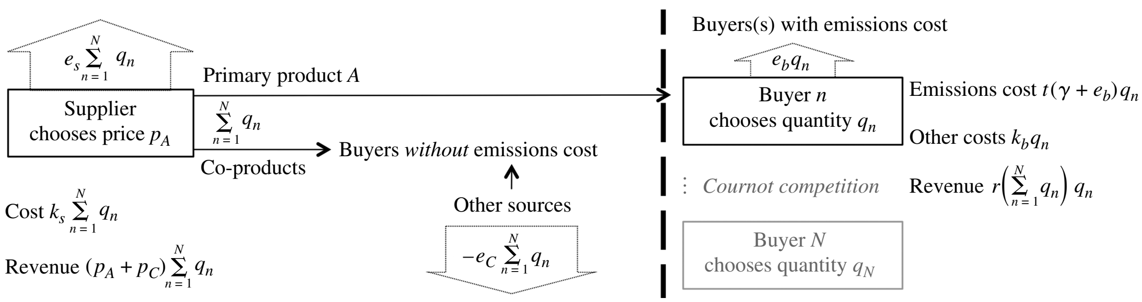
$$\gamma_X = e_s - \sum_{c=1}^{N_C} e_c. \tag{3}$$

The approach in (3) is conventionally called "system expansion" because, whereas (1) and (2) consider only the supplier's emissions e_s, (3) accounts for the reduction in emissions from other sources, $-\sum_{c=1}^{N_C} e_c$, per unit production by the supplier. However, for ease of parallel exposition, this paper refers to γ_V, γ_M and γ_X as value-, mass-, and expansion-based allocation, respectively. For brevity, the paper employs the notation

$$p_C \doteq \sum_{c=1}^{N_C} p_c, \quad \beta_C \doteq \sum_{c=1}^{N_C} \beta_c, \quad e_C \doteq \sum_{c=1}^{N_C} e_c$$

and focuses on the parameter region with $e_s \geq e_C > 0$ so $\gamma_X \geq 0$. Sections 4.1 and 4.2 demonstrate the calculation

Figure 1



of allocation rules γ_V, γ_M, and γ_X for cerium oxide and for palm oil, respectively; in those motivating examples, the suppliers have high emission intensity $e_s \gg e_C$. The assumption $e_C > 0$ is employed only in Proposition 8 and Corollary 1. Figure 1 illustrates the model.

Buyer n chooses order quantity q_n with the objective of maximizing its profit

$$r\left(\sum_{n=1}^{N} q_n\right) q_n - (k_b + p_A + t(e_b + \gamma)) q_n. \tag{4}$$

This paper adopts the standard assumptions that $r(q)$ is strictly decreasing and smooth, $r(Nq)q$ is strictly concave in q for $q \in [0, q_z)$, and $r(q) = 0$ for $q \geq q_z$, so there exists a unique equilibrium that is symmetric. Each buyer $n \in \{1, \ldots, N\}$ orders the quantity $\tilde{q}(p_A; \gamma)$ that is the unique solution to

$$r'(N\tilde{q})\tilde{q} + r(N\tilde{q}) - p_A - k_b - t(e_b + \gamma) = 0 \tag{5}$$

if $p_A \leq r(0) - k_b - t(e_b + \gamma)$ and otherwise orders $\tilde{q}(p_A; \gamma) = 0$.

The supplier sets the price p_A to maximize its profit

$$N\tilde{q}(p_A; \gamma)(p_A + p_C - k_s); \tag{6}$$

by assumption, $p_C < k_s$, so the supplier will not produce more than required to fill buyers' orders for product A. Let $\tilde{p}_A$ denote the equilibrium price that maximizes (6). The paper focuses on the parameter region in which the equilibrium quantity $\tilde{q}(\tilde{p}_A; \gamma)$ is strictly positive in the absence of border adjustment

$$r(0) > k_s - p_C + k_b + te_b, \tag{7}$$

and, under border adjustment with value-based allocation, the supplier's objective function (6) has a unique stationary point that is a global maximizer.

Note that a buyer's emissions $e_b\tilde{q}(\tilde{p}_A; \gamma)$, the supplier's emissions $e_s N\tilde{q}(\tilde{p}_A; \gamma)$, and the reduction in emissions by other firms due to the supplier's production of co-products $e_C N\tilde{q}(\tilde{p}_A; \gamma)$ all are proportional to a buyer's equilibrium order quantity $\tilde{q}(\tilde{p}_A; \gamma)$, which is a function of γ. Furthermore, the assumption $e_s \geq e_C$ implies that the industry makes a net positive contribution to global greenhouse gas emissions

$$(e_b + e_s - e_C)N\tilde{q}(\tilde{p}_A; \gamma) \tag{8}$$

that is also proportional to the buyer's equilibrium order quantity $\tilde{q}(\tilde{p}_A; \gamma)$. Propositions in §3 state results regarding "emissions," which may be interpreted as a buyer's emissions, the supplier's emissions, or the industry's net contribution to global greenhouse gas emissions (8); when one increases, the others do, too.

The model also represents a situation without government-imposed climate policy, wherein a buyer nevertheless faces some cost of emissions. For example, the cost of emissions t could be interpreted as the price of a voluntary offset credit; the Interface and GM examples in §1 demonstrate that a buyer may voluntarily commit to offset its total supply chain emissions (so $\gamma > 0$ in (4)) or to offset only its direct or downstream emissions (so $\gamma = 0$ in (4)). Alternatively, t could be the "shadow price" described in CDP (2013), the marginal cost of emission reduction for a multiproduct firm, like Walmart or PepsiCo, with a constraint on aggregate emissions associated with all its products. In that scenario, (4) represents the profit associated with one of those products. To enable the emissions associated with that product, the multiproduct firm must reduce its other emissions, and the cost of doing so is reflected in the terms with the factor t in (4). The constraint may apply to the firm's total supply chain emissions (so $\gamma > 0$ in (4)), as for Walmart, or only to the firm's direct emissions (so $\gamma = 0$ in (4)), as for PepsiCo.

Therefore, although Propositions in §3 use the term "border adjustment" to refer to the change from $\gamma = 0$ to $\gamma \in \{\gamma_V, \gamma_M, \gamma_X\}$ in (4)–(6), that may also be interpreted as a buyer's commitment to reduce or offset its supply chain emissions.

3. Results

One might expect that a border adjustment emissions tax on product A would reduce buyers' profits, reduce their order quantities, and hence reduce emissions. Indeed, within the WTO, the legality of border adjustment rests on that reduction in emissions (Fischer and

Fox 2012). Proposition 1 confirms that implementing border adjustment with expansion- or mass-based allocation reduces emissions and buyers' profits. However, implementing border adjustment with value-based allocation can have the opposite effect.

Proposition 1. (a) *Border adjustment with value-based allocation strictly increases emissions and each buyer's profit if the buyers' inverse demand function and variable cost satisfy*

$$r'''(Nq) \in (\underline{\xi}, \bar{\xi}] \quad \text{for } q \in [q_0, \bar{q}] \text{ and } k_b > \underline{k}, \tag{9}$$

where q_0 is a buyer's equilibrium order quantity in the absence of border adjustment, $\bar{q} > q_0$, and $\bar{\xi} > \underline{\xi}$. Border adjustment with value-based allocation strictly reduces emissions and each buyer's profit if

$$r'''(Nq) < \underline{\underline{\xi}} \quad \text{for } q \in [\underline{q}, q_0] \text{ and } k_b > \underline{k}, \tag{10}$$

where $\underline{\underline{\xi}} < \underline{\xi}$ and $\underline{q} < q_0$.

(b) *Border adjustment with expansion- or mass-based allocation always strictly reduces emissions and buyers' profits.*

To understand how and when border adjustment with value-based allocation can increase emissions and each buyer's profit, consider the case of isoelastic demand $r(q) = q^{-1/\epsilon}$, in which r''' increases with elasticity ϵ for q not extremely large. Hence, the bounds on r''' in (9) mean that demand is elastic, but not extremely so. When demand is elastic, reduction in a buyer's unit procurement cost stimulates a large increase in the buyer's order quantity, so border adjustment with value-based allocation motivates the supplier to make a large reduction in p_A to reduce the buyer's effective unit procurement cost $p_A + te_s p_A/(p_A + p_C)$. Hence, $p_A + te_s p_A/(p_A + p_C)$ can be smaller than the equilibrium p_A in the absence of border adjustment. That increases a buyer's profit and order quantity, and thus increases emissions. However, if the elasticity of demand is extremely high, the equilibrium p_A in the absence of border adjustment is so close to the supplier's effective production cost $k_s - p_C$ that the supplier cannot reduce p_A enough to make $p_A + te_s p_A/(p_A + p_C)$ smaller than the equilibrium p_A in the absence of border adjustment. For a case with $k_b + te_b = 0$, the last page of the electronic companion (available as supplemental material at http://dx.doi.org/10.1287/msom.2015.0572) proves that border adjustment with value-based allocation increases emissions and each buyers profit if $\epsilon \in (\underline{\epsilon}, \bar{\epsilon})$, where $\underline{\epsilon} < \bar{\epsilon}$. In other words, with isoelastic demand, the bound $k_b > \underline{k}$ in (9) is not necessary.

With general $r(q)$, the bound $k_b > \underline{k}$ in (9) serves to make the equilibrium quantity in the absence of border adjustment small, which motivates the supplier make a larger reduction in p_A in response to border adjustment, which tends to increase emissions and each buyer's profit.

Nevertheless, Proposition 1(a) (10) establishes that, even if $k_b > \underline{k}$, border adjustment with value-based allocation strictly decreases emissions and each buyer's profit when $r'''(q)$ is small, for aggregate order quantities q below the level in the equilibrium without border adjustment. Intuitively, when demand is inelastic, the supplier has little incentive to respond to the border adjustment by reducing p_A to reduce the buyer's effective unit procurement cost $p_A + te_s p_A/(p_A + p_C)$.

Imposing a border adjustment with expansion- or mass-based allocation causes the supplier to reduce p_A when $r'''(Nq)$ is not too large for $q \in [\hat{q}, q_0]$, where $\hat{q}$ is a constant. However, the proof of Proposition 1(b) shows that that reduction is smaller than the emissions cost per unit product, $\gamma_i t$ for $i \in \{M, X\}$, so the border adjustment reduces each buyer's equilibrium order quantity and hence emissions.

The Greenhouse Gas Protocol, ISO 14041, PAS 2050 emission accounting standards give a buyer the flexibility to choose among the allocation rules $\{\gamma_V, \gamma_M, \gamma_X\}$. Requiring a buyer to use the largest of those allocation rule would, in effect, maximize the buyer's emissions tax per unit product. Nevertheless, that could increase emissions and the buyer's profit.

Corollary 1. *Suppose* (9) *and $p_C < k_s \min\{\beta_C/(\beta_A + \beta_C), e_C/e_s\}$. Border adjustment with a requirement to use the largest allocation rule $\max\{\gamma_V, \gamma_M, \gamma_X\}$ strictly increases emissions and each buyer's profit compared to* (a) *the scenario without border adjustment and* (b) *the status quo flexibility for the buyer to choose among γ_V, γ_M, and γ_X.*

The rationale is that when p_C is small, the largest allocation rule is value-based allocation, and, with the status quo flexibility, a buyer maximizes its ex post (after the supplier sets p_A) profit by choosing the minimum of the expansion- and mass-based allocation rules. As established in Proposition 1(a), requiring the buyer to use the largest allocation rule (value-based allocation) motivates the supplier to drop its price and thus increases emissions and the buyer's profit under (9).

Note that (9) does not hold at $p_C = 0$, which means that the "counterintuitive" results, Proposition 1(a), Corollary 1, and Proposition 2 below, all rely on co-production.

Under more general conditions than (9), with border adjustment and value-based allocation, an increase in t (which may represent the tax per unit emissions, or the permit price in a cap-and-trade system) increases emissions from the industry in our model and buyers' profits.

Proposition 2. *Under border adjustment with value-based allocation, an increase in the cost per unit emissions t strictly increases emissions and each buyer's profit if $r'''(N\tilde{q}(\gamma_V; t)) \in (\underline{\nu}, \bar{\xi}]$ and $k_b > \underline{\kappa}$, where, in comparison with the constants $\underline{\xi}$ and $\underline{k}$ from Proposition 1, $\underline{\nu} \le \underline{\xi}$ and $\underline{\kappa} < \underline{k}$.*

3.1. Buyer Profit Maximization

Propositions 1 and 2 have important implications for buyers. In the absence of climate policy, a buyer can increase its profit by making a voluntary commitment to reduce or to offset its total supply chain emissions (like Walmart and Interface have done, as described in §1), as opposed to making a commitment regarding only its direct emissions (like PepsiCo has done). For a buyer that does so, Proposition 2 shows that the buyer's profit can potentially be increased by a commitment to purchase only from an expensive category of offset credits or to make deeper cuts in its supply chain emissions, thus increasing t. (Peters-Stanley and Gonzalez 2014 describe the various categories and associated prices for offset credits.)

A buyer might impose a voluntary tax on its supply chain emissions and use the tax revenue to purchase offsets. (In reality, to the best of our knowledge, no buyer yet does so, but Microsoft and Walt Disney voluntarily tax their own direct emissions and use the revenue to purchase offsets (Peters-Stanley and Gonzalez 2014).) Thus, a buyer might optimize its cost per unit emissions t. Relaxing the base model assumption that t is exogenous, the next proposition allows for the buyer to choose t and the allocation rule before the supplier sets the price p_A.

Proposition 3. *If a buyer could choose the cost per unit emissions t and the allocation rule to maximize its profit, value-based allocation would be optimal.*

The rationale is that with expansion- or mass-based allocation, $t = 0$ is optimal, and value-based allocation with $t = 0$ yields the same profit. Condition (9) is sufficient, but not necessary, for the buyer to achieve strictly greater profit with value-based allocation and $t > 0$.

Proposition 4 identifies a buyer's optimal allocation rule under border adjustment with exogenous t.

Proposition 4. *The allocation rule that maximizes a buyer's profit is either value-based allocation or the smaller of expansion- and mass-based allocation. The latter occurs if the value of co-products generated per unit production is sufficiently small, $p_C \le \underline{p}_C$.*

The rationale is that for *fixed* p_A, the buyer's profit would be maximized with the smallest allocation, which is value-based allocation if and only if $p_C \ge p_A \max\{e_C/(e_s - e_C), \beta_C/\beta_A\}$ and otherwise is the smaller of expansion- and mass-based allocation. Value-based allocation may maximize the buyer's profit at somewhat lower levels of p_C by motivating the supplier to reduce p_A. However, if $p_C \approx 0$, then $\partial\gamma_V/\partial p_A \approx 0$, meaning that when p_C is small, the supplier has little incentive to reduce p_A to reduce the value-based allocation γ_V. Hence, for sufficiently small p_C, the smaller of expansion- and mass-based allocation is optimal.

In the steel and chemical examples in Lee (2012) and the cerium oxide and palm oil examples in §4, the supplier is highly emission intensive and has co-products with relatively low value. For such suppliers, Proposition 4 (and the fact that high emission intensity $e_s \ge e_C(\beta_A + \beta_C)/\beta_C$ is equivalent to $\gamma_M \le \gamma_X$) imply that mass-based allocation γ_M is optimal for a buyer.

In general, regarding the choice of allocation rule, buyers' financial incentives are contrary to the environmental good. The next proposition holds whether t is exogenous or optimized by the buyer as in Proposition 3.

Proposition 5. *The allocation rule (and level of the tax per unit emissions) that maximizes a buyer's profit also maximizes emissions. The allocation rule (and level of the tax per unit emissions) that minimizes emissions also minimizes a buyer's profit.*

The caveat is that by purchasing offsets for its supply chain emissions, a buyer might cause a reduction in greenhouse gas emissions that is not represented in the model. Recall that "emissions" in all propositions in this paper may be interpreted as a buyer's direct emissions, the supplier's emissions, or the industry's net contribution to global greenhouse gas emissions (8).

3.2. Welfare Maximization for the Region with Climate Policy

The government of a region with climate policy, in deciding whether and how to implement border adjustment, should maximize social welfare for the region with climate policy, which includes buyers' profits, consumer surplus, government revenue from taxing emissions, and the social cost of emissions:

$$
\begin{aligned}
&(r(N\tilde{q}) - \tilde{p}_A - k_b - t(e_b + \gamma))N\tilde{q} \\
&\quad + \left(\int_0^{N\tilde{q}} r(u)\,du - r(N\tilde{q})N\tilde{q}\right) \\
&\quad + t(e_b + \gamma)N\tilde{q} - \delta(e_s + e_b - e_C)N\tilde{q} \\
&= \int_0^{N\tilde{q}} (r(u) - \tilde{p}_A - k_b - \delta(e_s + e_b - e_C))\,du. \qquad (11)
\end{aligned}
$$

By choosing $\gamma = 0$ (no border adjustment) or by imposing border adjustment with allocation rule $\gamma \in \{\gamma_V, \gamma_M, \gamma_X\}$, the government influences the supplier's equilibrium price $\tilde{p}_A$ and the buyer's equilibrium order quantity $\tilde{q}$ in (11) according to (4)–(6). The supplier's profit is not included in (11) because the supplier is foreign, operating outside the region with climate policy. In contrast, the industry's net contribution to global emissions $(e_s + e_b - e_C)N\tilde{q}$ appears in (11) because greenhouse gases are mixed in the atmosphere and have the same consequences regardless of where the emissions occur. The parameter δ represents the social cost per unit emissions. (Policy makers commonly use an estimate of δ in dollars per tonne CO_2 based on extensive research by climate scientists and economists to predict how greenhouse gas emissions will impact future climate and hence societal welfare. Estimating δ requires assignment of a dollar cost to loss of species and other noneconomic damages from climate change, and choice of the discount factor for future damages, both of which are contentious. Greenstone et al. (2013) describe the process of choosing δ for use in planning by the U.S. government.)

Proposition 6. *If the government could choose the industry-specific tax per unit emissions t and allocation rule to maximize social welfare* (11), *implementing border adjustment with value-based allocation would be socially optimal.*

The intuition is that value-based allocation (by motivating the supplier to reduce p_A to reduce the effective tax per unit on product A) allows the government to collect the greatest amount of revenue for any target unit cost for a buyer $\tilde{p}_A + k_b + t(e_b + \gamma)$; that unit cost for the buyer determines the order quantity and hence determines all the other components of social welfare (buyers' profits, consumer surplus, and the social cost of emissions).

However, under WTO rules, a government *cannot* implement border adjusment with the industry-specific optimal tax per unit emissions. Instead, as documented in §1, a border adjustment must apply the same tax per unit emissions (or permit price) for imports that is in effect in the domestic economy (Tamiotti et al. 2009). Hence, t is an exogenously specified parameter, corresponding to the emissions tax or emissions permit price for all regulated domestic industries, not optimized jointly with the choice of allocation rule. In contrast to Proposition 6, the next two propositions establish that with exogenous t, expansion-, mass-, or value-based allocation may be socially optimal, depending upon industry-specific parameters.

Proposition 7 shows that the region with climate policy should implement border adjustment with the allocation rule that minimizes emissions if the social cost per unit emissions δ is sufficiently large. To characterize the threshold on δ, it assumes

$$e_s\left(1-\max\left\{\frac{\beta_A}{\beta_A+\beta_C}, \frac{p_A}{p_A+p_C}\right\}\right) \geq e_C, \qquad (12)$$

which holds in highly emission-intensive industries (the primary candidates for border adjustment, in reality), including the cerium oxide and palm oil examples in §4.

Proposition 7. *Social welfare in the region with climate policy* (11) *is maximized with border adjustment and the allocation rule that minimizes emissions if and only if*

$$\delta \geq \underline{\delta}. \qquad (13)$$

Assuming (12), *fixed* p_A, *and sufficiently many buyers,*

$$\underline{\delta} \leq t. \qquad (14)$$

If (12) did not hold, then either γ_V or γ_M would exceed $e_s - e_C$, i.e., either the value- or mass-based allocation to product A would exceed the net emissions caused by the supplier's production of A. Hence, the social cost of emissions δ might need to be larger than t to make border adjustment with the emission-minimizing allocation rule socially optimal, i.e., (14) might not hold. That also might occur due to imperfect competition. A monopolist buyer would order a small quantity to sell at a high price, reducing emissions and consumer surplus. Value-based allocation, by motivating a monopolist supplier to drop its price p_A, might maximize welfare even when it does not minimize emissions. Hence, due to imperfect competition, δ must be relatively larger to make border adjustment with the emission-minimizing allocation rule socially optimal. Nevertheless, (14) holds in the cerium oxide example in §4, despite its price-setting monopolist supplier and small number of oligopolistic buyers.

In reality, the social cost per unit emissions δ is large relative to a buyer's cost per unit emissions t,

$$\delta > t. \qquad (15)$$

For example, the U.S. government recently adopted an estimate of $\delta = \$36$ per tonne CO_2 and acknowledged that the true social cost of emissions δ could be much higher and that δ will increase over time (Plumer 2013, Interagency Working Group on Social Cost of Carbon 2013, Greenstone et al. 2013). The cost per unit emissions t is relatively small, in that the U.S. government has not yet imposed an emissions tax or cap-and-trade system, and the global average price of a voluntary offset credit (a majority of which were purchased by U.S.-based firms) was only $t = \$3.8$/tonne CO_2 in 2014, with a general tendency to decline over the years (Peters-Stanley and Gonzalez 2014). Australia recently repealed its emissions tax. Even in countries that have an emissions tax or cap-and-trade system, the cost per unit emissions is low, e.g., $t = \$2$/tonne CO_2 in Japan, $t = \$5$/tonne CO_2 in South Africa (World Bank 2014), and $t = \$7.54$/tonne CO_2 on average in the European Union in 2014 (European Energy Exchange 2015).

Proposition 7 and (15) suggest that government should implement border adjustment with the allocation rule that minimizes emissions, at least for competitive, emission-intensive industries. Proposition 8 identifies the allocation rule that minimizes emissions.

Proposition 8. *The allocation rule that minimizes emissions is* (a) *expansion-based allocation if the supplier's emission intensity is large,* $e_s \geq \underline{e}_s$; (b) *value-based allocation if the value of co-products generated per unit production is small,* $p_C \leq \bar{p}_C$; (c) *mass-based allocation if the mass of co-products generated per unit production is small,* $\beta_C \leq \bar{\beta}_C$.

The rationale is that when the supplier's emission intensity e_s is large (as in the cerium oxide and palm oil examples in §4) the expansion-based allocation γ_X is correspondingly larger than the value- and mass-based allocations γ_M and γ_V, and assigns the highest effective tax per unit product A, which tends to reduce emissions. When a supplier has only a low-value "by-product" (as in the steel and chemicals industry examples in Lee (2012)) so $p_C \approx 0$, then $\gamma_V \approx e_s > \max\{\gamma_M, \gamma_X\}$, meaning that value-based allocation imposes the highest effective tax per unit product A, and $\partial\gamma_V/\partial p_A \approx 0$, meaning that the supplier has little incentive to reduce p_A to reduce γ_V, so value-based allocation minimizes emissions. Note that p_C is small to the extent that the supplier generates only a small mass of co-products per unit production of its primary product A and the co-products have little value per unit mass. Mass-based allocation minimizes emissions when the supplier generates only a small mass of co-products per unit production, yet those co-products have relatively high value per unit mass.

The last paragraph of §3.4 provides a stronger version of Proposition 8 for a setting with perfect competition among suppliers, with closed-form expressions for $\underline{e}_s$, $\bar{p}_C$, and $\bar{\beta}_C$.

3.3. Supplier Process Improvement

Now suppose that through investment or process improvement effort, the supplier can reduce its unit cost or emission intensity of production. The next proposition examines the supplier's "incentive" to do so, i.e., the increase in the supplier's profit resulting from such a process improvement.

Proposition 9. (a) *Border adjustment with value-based allocation strictly increases the supplier's incentive to reduce the production cost k_s if* (9), *but strictly reduces that incentive if* (10). (b) *Border adjustment with expansion- or mass-based allocation strictly reduces the supplier's incentive to reduce k_s.* (c) *Border adjustment with value-, expansion-, or mass-based allocation strictly increases the supplier's incentive to reduce its emission intensity e_s.*

Proposition 9(a) reinforces Proposition 1(a). Under value-based allocation and condition (9), by motivating the supplier to reduce the production cost k_s, a border adjustment can yield an even greater increase in emissions and the buyer's profit. The rationale is that reduction in k_s translates to reduction in the price p_A for a buyer, in equilibrium.

Even if condition (9) does not hold, border adjustment with value-based allocation might increase emissions and each buyer's profit, by motivating the supplier to incur a fixed cost to improve its energy efficiency, thereby reducing both the emission intensity e_s and production cost k_s. In fact, that occurs in a plausible extension of the cerium oxide numerical example in §4.1; details are available from the authors.

3.4. Competition

All propositions in this paper hold with perfect competition among buyers (in the limit as the number of buyers $N \to \infty$ or with $N \geq 2$ buyers that compete by setting prices) except those regarding buyers' profits; with perfect competition, buyers have zero profit. Furthermore, with price competition among buyers, Proposition 7 is stronger in that (14) holds with any $N \geq 2$ buyers. The aggregate import quantity, emissions, suppliers' profits, consumer surplus, and social welfare are the same with buyer price competition as in the limit in the base model with quantity competition as the number of buyers $N \to \infty$. All claims in this subsection regarding results that occur under perfect competition are straightforward to verify.

Consider an extension with quantity competition among $N_s \geq 1$ identical suppliers. In a simultaneous-move game, each supplier chooses a production quantity. Then the price per unit of product A, p_A, is determined by the equilibrium condition that buyers' aggregate demand for product A equals suppliers' aggregate production quantity. We restrict attention to symmetric equilibria in suppliers' quantities. This is an extension because for a monopolist supplier ($N_s = 1$), choosing the quantity is equivalent to choosing the price.

All propositions in this paper hold in this extension with quantity competition among suppliers. The caveat is that the proofs of Propositions 1(a), 2, and Proposition 9(a) are for a setting with $r(q) = q^{-1/\epsilon}$, perfect competition among buyers, and $k_b + te_b = 0$, and assume the existence of a unique symmetric equilibrium under value-based allocation. We derive the necessary and sufficient condition under which border adjustment with value-based allocation strictly increases emissions, a buyer's profit, and a supplier's incentive to reduce its production cost. That parameter region is nonempty for any finite number of suppliers N_s, but its measure decreases with N_s, and it vanishes in the limit as $N_s \to \infty$. (See the Multiple Suppliers section of the electronic companion for details.)

Indeed, imperfect competition among suppliers is necessary for the "counterintuitive" results, Proposition 1(a), Propositions 2, and 9(a). These results rely on suppliers increasing production to reduce p_A and the value-based allocation. However, with perfect competition ($N_s \to \infty$ or price competition), $p_A = k_s - p_C$, and suppliers earn zero profit, regardless of the allocation rule.

Therefore, with perfect competition among suppliers, implementing border adjustment or increasing the cost per unit emissions t will always strictly reduce emissions and buyers' profits. Furthermore, stronger versions of Propositions 4 and 8 hold. The allocation rule that maximizes a buyer's profit is the smallest allocation rule, which is value-based allocation if and only if $p_C \geq k_s \max\{\beta_C/(\beta_A + \beta_C),\ e_C/e_s\}$, and otherwise it is the smaller of expansion- and mass-based allocation. The allocation rule that minimizes emissions is the largest of the allocation rules. It is expansion-based allocation if and only if $e_s \geq e_C \max\{k_s/p_C, (\beta_A+\beta_C)/\beta_C\}$, is value-based allocation if and only if $p_C \leq k_s \min\{\beta_C/(\beta_A+\beta_C), e_C/e_s\}$, and it is mass-based allocation if and only if $\beta_C \leq \beta_A \min\{p_C/(k_s-p_C), e_C/(e_s-e_C)\}$. The status quo flexibility to choose the allocation rule is optimal for buyers to the detriment of the environment: each buyer maximizes its profit by choosing the smallest of the allocation rules, which maximizes emissions.

4. Numerical Examples

Section 4.1 presents a numerical example based on cerium oxide imports by U.S. flat glass manufacturers. Section 4.2 presents a numerical example based on palm oil imports by EU margarine manufacturers. The two numerical examples are remarkably different in that the former has a monopolist supplier, whereas the latter assumes perfect competition among suppliers. In the former, the expansion-, mass-, and value-based allocations differ greatly, whereas in the latter they are nearly equal. Nevertheless, in both examples, the choice of allocation rule has a large-in-magnitude impact on emissions, buyers' profits, and social welfare.

4.1. Cerium Oxide Imports by U.S. Flat Glass Manufacturers

Consider a numerical example based on imports of cerium oxide by the U.S. flat glass industry, comprised of $N=6$ firms (NSG Group 2010). Producing 250 kg of flat glass requires 1 kg of cerium oxide as an essential polishing agent (Hadley et al. 2011, Nashed 2006) and directly emits $e_b = 152.5$ kg of CO_2 (Ecofys Consulting 2009). The price-setting supplier of cerium oxide, Baotou Rare Earth Company, mines rare earth oxides, predominantly cerium oxide, with iron ore in a constant ratio at its Bayan Obo mine located in Inner Mongolia (Stanway and Hopfner 2011, Yong 2011). Baotou incurs a variable cost of $k_s = \$48$ (BlackRock 2011, Humphries 2011) and emits $e_s = 12{,}900$ kg CO_2 (Bouorakima 2011) in producing $\beta_A = 1$ kg of cerium oxide and $\beta_C = 245$ kg of iron ore (at 62% iron concentration; British Geological Survey 2011, China Mining Association 2011). Baotou's emissions are high from mining operations, separation of rare earth oxides (which requires dozens of chemical processes at temperatures above 500 °C), and additional processing of the residual iron ore to increase its iron concentration to the marketable level of 62% (Schler et al. 2011). Other firms that produce iron ore at 62% concentration emit only, on average, $e_C = 331$ kg CO_2 per 245 kg iron ore (Lubetsky and Steiner 2006), so the expansion-based allocation (3) for cerium oxide is $\gamma_X = e_s - e_C = 12{,}569$ kg CO_2 per kg cerium oxide, which is 97% of Baotou's emissions e_s. In 2011, Baotou charged U.S. buyers approximately $p_A = \$150$/kg cerium oxide (MetalPrices 2011) and sold iron ore at the prevailing market price of \$180/tonne (Blas 2011) in China, corresponding to $p_C = \$44$ for 245 kg of iron ore. (Baotou has a negligible share of China's iron ore market.) We estimate the 2011 import volume of cerium oxide by U.S. flat glass manufacturers to be 681,200 kg, based on a moving average of the total U.S. imports of cerium oxide from 2006 to 2010 (United Nations 2011) and the fraction used in flat glass manufacturing (Credit Suisse 2011, Hocquard 2010); assuming that to be the Cournot equilibrium quantity under a linear demand function and $t=0$, we fit the parameters $x-k_b = 1{,}184.4$ and $y = 0.0029$. Varying t and the allocation rule under border adjustment, assuming that the supplier Baotou sets p_A to maximize its profit from sales to the flat glass manufacturers, we calculate the resulting emissions and profit for the flat glass manufacturers ("buyers" in our model), which are shown in Figure 2.

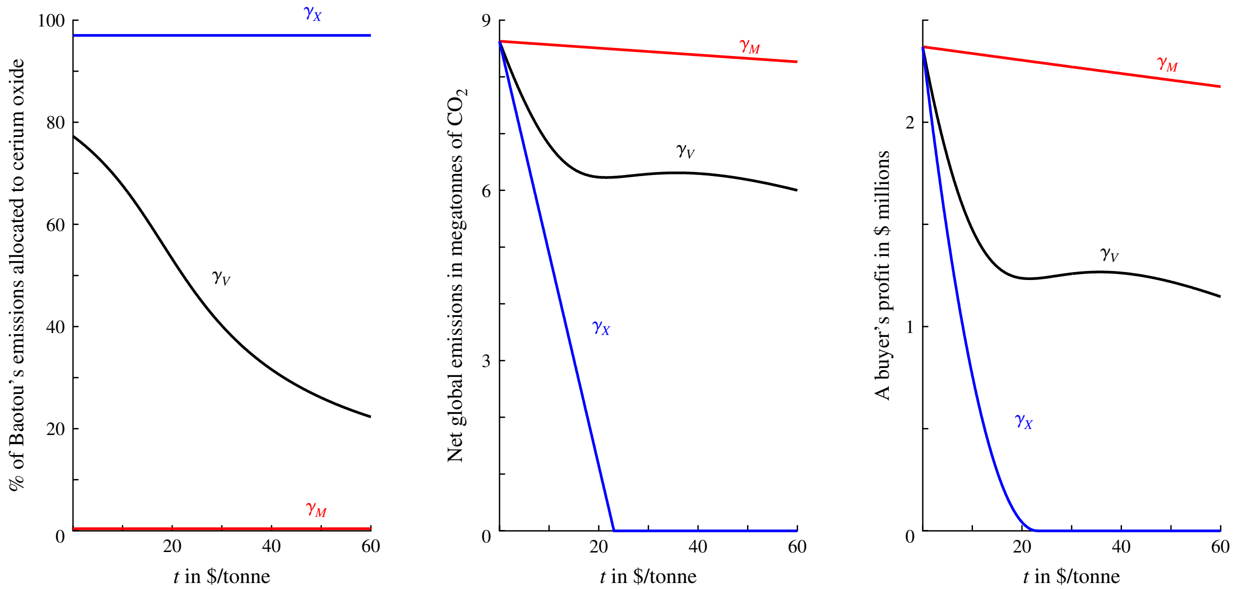
As predicted by Proposition 2, Figure 2 shows that under value-based allocation, emissions and buyers' profits increase with the emissions cost t as it ranges from \$21.5 to \$35.7 per tonne CO_2.

Figure 2 also shows that emissions are minimized with expansion-based allocation, as suggested by Proposition 8, because Baotou's emission intensity e_s is large. Therefore, according to Proposition 8 and as is evident in Figure 2, buyers' profits are minimized with expansion-based allocation and are maximized with the mass-based allocation that maximizes emissions.

Regarding social welfare, for all $t>0$, the threshold parameter $\underline{\delta}$ in Proposition 7 satisfies $\underline{\delta} \leq t$. Hence, according to Propositions 7, U.S. welfare is maximized by implementing border adjustment with the expansion-based allocation rule that minimizes emissions, for any $t \leq \delta$. Indeed, in this example, at the U.S. estimated social cost $\delta = \$36$ per tonne CO_2, U.S. welfare is maximized by implementing border adjustment with expansion-based allocation for *all* $t>0$, not only for $t \leq \$36$.

The allocation rule has a large impact on emissions, buyers' profits, and social welfare. Under mass-based allocation (or, equivalently, the status quo flexibility for a buyer to choose the allocation rule), emissions and buyers' profits are nearly as high as without border adjustment; even at $t = \$60$ per tonne CO_2, emissions persist at 8.36 megatonnes of CO_2, only 1% lower than without border adjustment. That 8.36 megatonnes of CO_2 is equivalent to the U.S. average annual emissions from 1.78 million cars. In contrast, even at only $t = \$10$ per tonne CO_2 (the lower bound on the price of an emission permit in California; California Air Resources Board 2013), emissions are 43% lower under expansion-based allocation and 21% lower under value-based allocation than under mass-based allocation; buyers' profits are 67% lower under expansion-based

Figure 2 (Color online) Percentage of Allocated Emissions, Net Global Emissions, and a Buyer's Profit in Cerium Oxide Example



Notes. The first panel shows the percentage of Baotou's CO_2 emissions allocated to cerium oxide under expansion-based (γ_X), value-based (γ_V), and mass-based (γ_M) allocation rules. The second panel shows the estimated net annual contribution to global CO_2 emissions, including emissions from Baotou's mining and processing of cerium oxide (and co-product iron ore) to supply U.S. flat glass manufacturers, the corresponding reduction in emissions by other firms that produce iron ore, and the emissions from production by U.S. flat glass manufacturers. The third panel shows the estimated annual profit for a U.S. flat glass manufacturer.

allocation and 37% lower under value-based allocation than under mass-based allocation. Above $t = \$23$ per tonne CO_2, emissions and buyers' profits are zero under expansion-based allocation (the Australian tax on emissions was $24 per tonne CO_2 during 2013 through July 2014 (Robson 2013)). At the U.S. estimated social cost $\delta = \$36$ per tonne CO_2, the industry generates net negative U.S. welfare in the status quo (with no border adjustment or with flexibility for buyers to choose mass-based allocation). Border adjustment with expansion-based allocation eliminates that negative welfare impact for any t above $24 per tonne CO_2, whereas even at $t = \delta = \$36$ per tonne CO_2, imposing border adjustment with value-based allocation reduces that negative welfare impact by only 54%.

As an alternative to the expansion-, value-, or mass-based allocation rules, Granot et al. (2014) recommend Shapley value allocation, which in this example is $\gamma_X/2$. Interestingly, although value-based allocation γ_V is strictly greater than the Shapley value allocation $\gamma_X/2$, emissions and buyers' profits are strictly greater under the value-based allocation γ_V than under the Shapley value allocation $\gamma_X/2$, for all t between $9 and $23 per tonne CO_2. This is an example of the phenomenon in Corollary 1: requiring buyers to use a larger allocation rule (value-based allocation) increases emissions and the buyers' profits.

4.1.1. Setting Prices for Multiple Co-Products Sold in Region with Climate Policy. For simplicity, we have focused on cerium oxide and iron ore. In reality, however, Baotou does mine other rare earth co-products in a fixed ratio with cerium oxide, including neodymium, worth only approximately 12% as much as the cerium oxide and iron ore per unit production, and other rare earths worth substantially less per unit production (Spooner 2005, MetalPrices 2011). Whereas our base model formulation assumes that the supplier sets the price only for its primary product (cerium oxide in this example) and sells all co-products in the local market without climate policy, in reality, Baotou has price-setting power for neodymium as well as cerium oxide, and Baotou sells some neodymium into regions with climate policy; notably, the EU. Joint optimization of the prices of neodymium and cerium oxide would be very challenging, similar to the optimization problem studied in Tomlin and Wang (2008) but with the added complexity of emission allocation. Under value-based allocation, reducing the price of cerium oxide increases the amount of emissions allocated to neodymium, which may reduce demand for neodymium. That counters the incentive to reduce the price of cerium oxide to reduce the value-based allocation to cerium oxide. Thus, selling a co-product into the region with climate policy, not just the primary product, might deter a supplier from increasing production and emissions in response to a border adjustment or increase in the cost per unit emissions t.

4.2. Palm Oil Imports by EU Margarine Manufacturers

Consider a numerical example based on imports of palm oil by the EU margarine industry, comprised of $N = 8$ firms (CBI 2009, Europe Economics 2014). Palm oil is produced in Malaysia and Indonesia with, according to the estimate in Schmidt (2010), emissions of $e_s = 3.52$ kg CO_2 and co-product masses of 0.129 kg palm meal and 0.038 kg of fodder fat for each kg of palm oil.[2] Hence, the mass-based allocation (2) is $\gamma_M = 3.52 \times (1/(1+0.129+0.038)) = 3.02$ kg CO_2 per kg of palm oil. The palm meal and fodder fat co-products, sold locally for animal feed, substitute for 0.002 kg of soybean meal and 0.176 kg of spring barley (Schmidt 2010), which have emission intensities of 0.721 kg CO_2 and 0.619 kg CO_2 per kg, respectively (Dalgaard et al. 2008, Niero et al. 2015). The emissions avoided by eliminating production of that soybean meal and spring barley is $e_C = 0.721 \times 0.002 + 0.619 \times 0.176 = 0.11$ kg CO_2 per kg palm oil, so the expansion-based allocation (3) is $\gamma_X = 3.52 - 0.11 = 3.41$ kg CO_2 per kg palm oil. We assume perfect competition among palm oil suppliers, so the selling price of palm oil, p_A, is fixed. We assume that $p_A = \$0.78$ per kg and the prices of palm meal and fodder fat are \$0.18 per kg and \$0.6 per kg. Those are the 2013 average prices for palm oil, palm meal, and fodder fat reported on IndexMundi,[3] Alibaba,[4] and by the Malaysian Palm Oil Council (2013), respectively. Combining those prices with the aforementioned co-product masses of 0.129 kg palm meal and 0.038 kg of fodder fat for each kg of palm oil, the value of the co-products is $p_C = 0.129 \times \$0.18 + 0.038 \times \$0.6 = \$0.046$ per kg palm oil, so the value-based allocation (1) is $\gamma_V = 3.52 \times (0.78/(0.78 + 0.046)) = 3.32$ kg CO_2 per kg palm oil. In the European Union, producing 1 kg margarine requires 0.237 kg palm oil and directly emits $e_b = 1.66$ kg CO_2 (Nilsson et al. 2010). Using the price elasticity of demand for margarine from Bouamra-Mechemache et al. (2008), EU production of margarine from palm oil in 2013 (European Margarine Association 2013, CBI 2009), and the 2013 average permit price $t = \$6$/tonne CO_2 (European Energy Exchange 2015) at the 2013 average exchange rate 1.3 \$/€, and assuming a linear inverse demand function $r(q) = x - yq$, we fit the parameters $x - k_b = \$88{,}499$ and $y = \$0.064$/kg.

Surprisingly, even with the extremely low $t = \$6$/tonne CO_2 (which drew criticism that the EU cap-and-trade system is ineffective (Morales and Vitelli 2013)) and even though the expansion-, value-, mass-based allocations are nearly the same, at 97%, 94%, and 86%, respectively, of a supplier's emissions e_s per unit production, the choice of allocation rule has a substantial impact on emissions and buyers' profits (and hence social welfare). Expansion-based allocation (the largest of the candidates) minimizes emissions and buyers' profits, whereas mass-based allocation (the smallest of the candidates) maximizes emissions and buyers' profits. The EU margarine manufacturers using palm oil would earn \$152 million greater annual profit under mass-based than expansion-based allocation. Imposing border adjustment with expansion-based allocation decreases the industry's net annual contribution to global emissions by 160,810 tonnes CO_2 (the annual CO_2 emissions from 114,368 cars in the European Union; International Council on Clean Transportation 2014, Green Car Congress 2015), 19,461 tonnes more than with mass-based allocation. Applied to all imports of palm oil, border adjustment and the choice of allocation rule could have a much larger impact because palm oil is a primary input to many other food products, detergents, cosmetics, lotions and other personal care products, industrial chemicals, and biofuels.

[2] "Palm oil" includes palm oil (from the fruit) and palm kernel oil, both of which are used in producing margarine. Because their market prices differ slightly, we weight those prices by the mass-ratio in which the oils are produced to calculate p_A.

[3] See, e.g., http://www.indexmundi.com/commodities/?commodity=palm-oil and http://www.indexmundi.com/commodities/?commodity=palm-kernel-oil (accessed September 20, 2015).

[4] See, e.g., http://www.alibaba.com/product-detail/Palm-Kernel-Meal_125818415.html?spm=a2700.7724838.30.16.FZhs6x (accessed September 10, 2015).

5. Concluding Remarks

Motivated by examples from emission-intensive basic material and agricultural industries, this paper has analyzed a model in which a supplier sells its primary product to a buyer that incurs an emissions cost and sells a co-product into a market without an emissions cost. The market price for the co-product is exogenous, whereas the more surprising insights require that the supplier influences the price for its primary product.

5.1. Insights for a Buying Firm

A buyer can potentially increase its profit by starting to incur a cost in proportion to its supply chain emissions, whether by lobbying for border adjustment or making a voluntary commitment to reduce or offset its supply chain emissions. That is profitable under value-based allocation and imperfect supplier competition, when demand for the buyer's product is elastic but not extremely so, and the buyer's unit operating cost is sufficiently large. Then, a supplier responds by innovating to reduce its production cost and/or lowering its selling price, to the extent that the buyer enjoys a lower procurement cost per unit, even including the new emissions cost.

Value-based allocation is optimal if a buyer can jointly optimize its cost per unit emissions, e.g., through a voluntary commitment to tax its supply chain emissions and use the revenue to purchase offsets. The caveat is that, perhaps, for a buyer with multiple, differentiated suppliers, a uniform tax per unit emissions cannot provide optimal incentives for all.

With an exogenous cost per unit emissions, either value-based allocation is optimal or the smaller of the expansion- and mass-based allocations is optimal. Mass-based allocation is optimal when the supplier is highly emission intensive and its co-products are substantially less valuable than its primary product, as in both examples in §4 and as in the examples in Lee (2012) of steel and chemical manufacturers that have converted process waste into a by-product. With perfect competition among suppliers, the minimum allocation rule is optimal. With imperfect competition among suppliers, value-based allocation may be optimal even when value-based allocation is the largest of the candidate allocation rules.

5.2. Insights for NGOs Designing Voluntary Emission Accounting Standards

To minimize emissions, rather than allow a buyer to choose the allocation rule, the environmental NGOs that administer the voluntary emission accounting standards should require system expansion when a supplier's emission intensity is very high, as in the cerium oxide and palm oil examples; value-based allocation when a supplier has only a low-value by-product, as in the steel and chemicals industries in Lee (2012); and mass-based allocation when a supplier's process generates little mass of co-product, but that co-product is highly valuable.

5.3. Insights for Climate Policy Makers

Commonly among states with an emissions tax or cap-and-trade system, the tax or permit price is substantially lower than the social cost per unit emissions. Proposition 7 suggests that such states should implement border adjustment for emission-intensive imports, with the industry-specific allocation rule that minimizes emissions (characterized in the paragraph above). That could substantially reduce global emissions and improve social welfare, as demonstrated by the rare earth and palm oil numerical examples. However, that will not be easy to accomplish. Importers will oppose the allocation rule that minimizes emissions (which also minimizes their profits), and specifying a distinct allocation rule for each emission-intensive industry with co-production obviously will complicate the legislation and implementation of border adjustment.

To simplify the legislation of border adjustment, an intuitively appealing approach would be to require the firms in emission-intensive industries with co-production to calculate the expansion-, mass-, and value-based allocations and use the maximum one. Alternatively, firms could be required to use value-based allocation, which is relatively simple to compute and, at present, used by most firms that account for their supply chain emissions (Granot et al. 2014, Brown et al. 2010). However, those appealingly simple approaches could be counterproductive. The maximum of the three candidate allocations would result in the minimum emissions under perfect competition. However, when the supplier has market power, as in the examples given in §1, value-based allocation can be the maximum of the three candidates and yet result in higher emissions than the status quo flexibility for a buyer to use the minimum allocation. Worse yet, imposing border adjustment with value-based allocation (or a requirement to use the maximum) might result in strictly higher emissions than the status quo with no border adjustment. That tends to occur under the condition that demand for the import is elastic but not extremely so, or might occur because the border adjustment motivates a supplier to invest in energy efficiency. Within the WTO, the legality of border adjustment rests on its benefit to the environment (Fischer and Fox 2012). Hence, a border adjustment with value-based allocation that increased emissions would violate WTO law. In contrast, border adjustment with the choice of allocation rule that minimizes emissions is legal under WTO rules.

Supplemental Material

Supplemental material to this paper is available at http://dx.doi.org/10.1287/msom.2015.0572.

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