CESifo WORKING PAPERS

7152 2018

July 2018

Multi-Pollutant Point-Nonpoint Trading with Participation Decisions: The Role of Transaction Costs

Carson Reeling, Richard D. Horan, Cloe Garnache

CESifo

Impressum:

CESifo Working Papers
ISSN 2364-1428 (electronic version)
Publisher and distributor: Munich Society for the Promotion of Economic Research - CESifo GmbH
The international platform of Ludwigs-Maximilians University's Center for Economic Studies and the ifo Institute
Poschingerstr. 5, 81679 Munich, Germany
Telephone +49 (0)89 2180-2740, Telefax +49 (0)89 2180-17845, email office@cesifo.de
Editors: Clemens Fuest, Oliver Falck, Jasmin Gröschl
www.cesifo-group.org/wp

An electronic version of the paper may be downloaded
· from the SSRN website: www.SSRN.com
· from the RePEc website: www.RePEc.org
· from the CESifo website: www.CESifo-group.org/wp

CESifo *Working Paper No. 7152*
Category 9: Resource and Environment Economics

Multi-Pollutant Point-Nonpoint Trading with Participation Decisions: The Role of Transaction Costs

Abstract

High transaction costs and thin participation plague water quality trading and prevent markets from delivering expected efficiency gains. Point sources generate a single pollutant, while nonpoint sources generate multiple, complementary pollutants. We develop a dynamic search model of point-nonpoint trading that includes transactions costs. These costs affect participation decisions and generate strategic complementarities with multiple large or small market participation levels equilibria. Integrated markets—with trading across pollutants—lead to lower transactions costs for both sources and a larger basin of attraction around the full-participation equilibrium, and thus may improve pollution trading efficiency relative to distinct markets.

JEL-Codes: D470, Q530, Q580.

Keywords: credit stacking, multi-pollutant trading, participation, strategic complementarities, transactions costs.

*Carson Reeling**
Department of Agricultural Economics
Purdue University
403 W. State Street
USA – West Lafayette, IN 47907
creeling@purdue.edu

Richard D. Horan
Department of Agricultural, Food, and Resource Economics
Michigan State University
446 W. Circle Dr.
USA – East Lansing, MI 48824-1039
horan@msu.edu

Chloe Garnache
Department of Agricultural, Food, and Resource Economics
Michigan State University
446 W. Circle Dr.
USA – East Lansing, MI 48824-1039
garnache@msu.edu

*corresponding author

Introduction

In theory, environmental pollution markets promote allocative efficiency by giving polluters opportunities to reduce their abatement costs. These opportunities have led to many highly successful applications to air pollutant control; the US sulfur dioxide (SO_2) market, which reduced acid rain at a much lower cost than anticipated with traditional command-and-control instruments, is the most prominent example (Stavins 1998). In contrast, few water quality markets have achieved predicted gains. Despite much effort, few water pollution markets in the United States are functioning (Fisher-Vanden and Olmstead 2013).

Many have pointed out that high transaction costs and thin participation have plagued water quality trading and prevented markets from delivering the expected efficiency gains (Ribaudo and Nickerson 2009; Woodward et al. 2002; Fisher-Vanden and Olmstead 2013). Most water quality trading programs do not operate under the traditional exchange market framework but rather rely on bilateral negotiations between permit buyers and sellers or on clearinghouses where an intermediary can facilitate trades, e.g., as in the Neuse River program in North Carolina (Woodward and Kaiser 2002; Woodward et al. 2002; Fisher-Vanden and Olmstead 2013). These features lead to transaction costs in the form of search and contracting costs.

The literature on efficient market design has generally assumed away the existence of firm-level transaction costs. The two prominent studies that do model transactions costs, Stavins (1995) and Montero (1997), assume these costs depend on the number of permits traded, independent of the number of trade partners. All of this work essentially assumes a fixed, large number of participants. This may not be a problem for traditional exchange markets with many potential participants whose emissions are easily traded due to their homogenous impacts. However, as described above, these assumptions do not hold for water quality markets, where trading is often restricted to a single watershed and emissions have spatially heterogeneous impacts.

We develop a dynamic search model of point-nonpoint trading that includes search and contracting costs. As in extant markets, trading occurs via bilateral negotiation: a point source that has previously been regulated (e.g., through the NPDES permit system) must find and contract with an unregulated nonpoint source to obtain pollution offsets. Each point source bears search and contracting costs that depend on the number of potential trading partners. The nonpoint source sector does not pay search costs, but may incur some contracting costs. These costs may affect participation decisions, which we model via replicator dynamics: participation increases over time as long as the net gains from doing so are positive.

We find transactions costs may generate strategic complementarities (i.e., a source of one type is more willing to participate when more sources of the other type participate) which, in turn, may generate multiple market equilibria. One equilibrium involves full participation by point and nonpoint sources. Here, a sufficient number of both types of polluters initially expect a thick market and thus have incentives to enter, reducing transactions costs and incentivizing more to enter. Markets fail to materialize in the second equilibrium. Here, a sufficient number of polluters initially expect a thin market and thus have fewer incentives to enter, increasing transactions costs so that the market eventually collapses.

Understanding how transaction costs affect market participation and outcomes can help identify market design weaknesses and assist policy makers in addressing the problem of thin markets. A possible remedy for low participation is multi-pollutant trading, or allowing polluters to trade across imperfectly-substitutable pollutants that cannot easily be converted into equivalent units. Indeed, many polluters generate multiple, linked pollutants (e.g., coal-fired power plants jointly emit SO_2 and NO_X). Interest in developing market-based approaches that allow trading across pollutants has been growing among academics and policy makers for several reasons. First, multi-pollutant trading has been shown to address inefficiencies that arise from separate regulations on linked pollutants (Ambec and Coria 2018; Lutter and Burtraw 2002; Reeling et al. 2018; Woodward 2011), particularly in the presence of pre-existing standards for linked pollutants (Cohen and Keiser 2017; Novan 2017). Second, and perhaps most importantly, multi-pollutant trading can mitigate market thinness by expanding the effective supply of permits from a single source (since permit suppliers who abate multiple, complementary pollutants can sell credits for each to the same permit buyer). This is reduces the required number of trading partners for regulated sources and, hence, reduces transaction costs.

We examine a case where nonpoint source polluters generate two complementary pollutants (such that the marginal cost of abating one pollutant decreases with abatement of the other), and there are two point source sectors—one emitting each pollutant. We examine several scenarios. First, we explore polluters' participation decisions for a single bilateral exchange market. Nonpoint sources can sell permits from abatement of only one pollutant. We then examine participation decisions under two distinct markets with credit stacking. Here, nonpoint sources can sell permits from abating each pollutant in separate markets. Finally, we compare these two market structures against an integrated market in which regulated polluters can meet their caps by holding permits generated from abatement of either pollutant. Permits from each source and pollutant are traded in a single, multipollutant market, as in Montero (2001). We show that abatement cost complementarities increase the gains to participation for nonpoint sources. This leads to lower search costs—and greater gains from trading—for point sources. Integrated trading generates a larger basin of attraction around the full-participation equilibrium and thus may improve the efficiency of pollution trading.

The Pollution Problem

Consider a region populated with two types of polluters, indexed by $i \in \{W, A\}$. Index W indicates point sources that emit water pollutants (nutrients), indexed by w. Index A indicates agricultural nonpoint sources that emit both greenhouse gases (GHGs), indexed by g, and nutrients.[1] We simplify matters by assuming each category of polluters comprises a fixed number of identical sources or firms, N_i. A type-i firm's emissions of pollutant $m \in \{g, w\}$ are denoted e_{im}. We use the indices i and m for generalized variables and relations that can apply to either point or nonpoint sources. For variables and relations that apply specifically to point sources, we use the single index w; the indices A and m are used for relations that apply specifically to nonpoint sources.

Pollution is generated as part of valuable production processes. Profits prior to regulation are given by the concave restricted profit function $\pi_i(\mathbf{e}_i)$, where $\mathbf{e}_A = [e_{Ag}\ e_{Aw}]$ and $\mathbf{e}_w = e_w$. These profits are initially increasing in each pollutant the firm generates, i.e.,

[1] There may also be point sources of GHG emissions within the region. However, for reasons described below, we do not model these sources.

$\partial\pi_i/\partial e_{im} > 0$ for smaller values of e_{im}. A firm's unregulated emissions levels, e_{im}^u, satisfy $\partial\pi_i/\partial e_{im} = 0$ and generate profits $\Pi_i^u \equiv \pi_i(\mathbf{e}_i^u)$. We assume the nonpoint source's emissions are jointly produced as complements, $\frac{\partial^2\pi_A}{\partial e_{Ag}\partial e_{Aw}} > 0$, which implies there are complementarities in abatement. Abatement complementarity follows Woodward's (2011) assumption and is consistent with empirical evidence for agricultural nutrients and GHGs (e.g., Vitousek et al. 1997).

Each pollutant is generated deterministically and is then uniformly mixed in the environment.[2] Damage costs for this region's emissions of pollutant *m* are given by the increasing function $D_w(\sum_i N_i e_{iw})$. Damage costs for water quality are concave. Damage costs for greenhouse gas emissions are linear since these damages depend on global emissions.

The Permit Market

We examine two types of pollution markets. The first is a developing nutrient market involving bilateral trades between point and nonpoint sources within the region. Bilateral trading is common in water quality markets (Woodward and Kaiser 2002) and requires that willing traders incur costs to locate and/or contract with each trading partner. We simplify matters by assuming prices do not depend on a bargaining process but instead are competitively determined by price-taking firms that have located partners. Prices in this market are determined locally.

The second market is a competitive GHG emissions market involving firms on a

[2] Deterministic, uniformly-mixed emissions is a stringent assumption when dealing with nonpoint sources, as spatial impacts and emissions uncertainties often arise in such settings. However, this assumption allows us to focus on the interaction between transactions costs and participation decisions in both distinct and multi-pollutant markets.

much broader scale, both within and outside of the region. Participating sources within the region do not have a collective influence on GHG prices; these prices are exogenously determined on a commodity exchange. Our assumptions about the GHG sector imply that nonpoint source trades of GHG emissions will not impact GHG permit prices (nor marginal damages), thereby having negligible impact on point source decisions in the GHG sector. This means there is no need to model GHG point sources and we can instead focus on nonpoint source participation.

We consider three market scenarios within this setting. The first, the "single market scenario," involves a single point-nonpoint market for nutrient emissions, with nonpoint sources unable to trade in the GHG market. The nutrient market involves source-specific permits with source-specific prices and a trade ratio guiding the terms of trade between these sources. The second scenario is the "distinct market" scenario, with nonpoint sources being allowed to trade in both markets. Each market in this scenario is distinct and involves a single pollutant. We assume nonpoint trades of GHG emissions occur on a one-for-one basis within GHG markets.[3] The third scenario is the "integrated market scenario" (e.g., Reeling et al. 2018) in which point source nutrient emitters can purchase either nutrient or GHG permits from nonpoint sources within one integrated market, with each type of trade governed by a separate trade ratio.

Let $\hat{e}_w$ denote the initial permit allocation to an individual point source. Only point sources are initially regulated, with $0 < \hat{e}_w < e_w^u$, whereas nonpoint sources are initially unregulated with implicit rights to emit either pollutant at their unregulated levels, i.e., $\hat{e}_{Am} = e_{Am}^u \; \forall m$. Accordingly, point sources are permit buyers so that $e_w \geq \hat{e}_w$, and

[3] This assumption is made for simplicity. Reeling et al. (2018) demonstrate that efficiency may be improved by requiring that trades occur at rates that differ from one-to-one.

nonpoint sources are sellers so that $\hat{e}_{Am} \geq e_{Am}\ \forall m$. We use weak inequalities here because transactions costs may keep some sources from participating in the market. We also assume initial permit levels are pre-specified; they are not regulatory choice variables for market designers. Horan and Shortle (2005; 2017) and Reeling et al. (2018) argue that this is consistent with existing point-nonpoint programs that utilize markets as a mechanism for voluntarily inducing nonpoint source abatement.

These assumptions allow us to write a point source's emissions as $e_w = \hat{e}_w + x_w$, where $x_w \geq 0$ is the source's demand for additional permits. A nonpoint source's emissions of pollutant m are $e_{Am} = \hat{e}_{Am} - x_{Am}$, where $x_{Am} > 0$ is the source's supply of permits. As $\hat{e}_{im}$ is fixed, we can write restricted profits as a function of demand or supply. Let $\pi_w(x_w)$ be point source profits, with $\pi_w'(x_w) > 0$ and $\pi_w''(x_w) < 0$. Likewise, let the concave function $\pi_A(x_{Aw}, x_{Ag})$ be nonpoint source profits, with $\partial\pi_A/\partial x_{Am} \leq 0$ and $\partial\pi_A^2/(\partial x_{Aw}\partial x_{Ag}) > 0$ due to abatement complementarities. Define the sector-specific prices for point and nonpoint source nutrient permits as v_w and v_{Aw}, respectively. The price of GHG emissions is v_g. This price is exogenously determined by the carbon exchange when nonpoint sources trade in this market; it is endogenously determined in an integrated market where nonpoint sources only trade with the point source (e.g., if the permit price offered by point sources is sufficiently large relative to the exogenous commodity market price).

Point-nonpoint nutrient trades may not occur at a one-to-one rate, as this may be optimal when permit levels are sub-optimally lax (Reeling et al. 2018). Also, one-for-one trades of different pollutants is unlikely to be optimal. Define $\tau_{Am,n}$ as the number of a nonpoint source type-m permits that must be purchased for a one-unit increase in a point source's emissions of pollutant *n*, or the terms of trade:

$$\tau_{Aw,w} = \left|\frac{dx_{Aw}}{dx_w}\right|, \quad \tau_{Ag,g} = \left|\frac{dx_{Ag}}{dx_g}\right|, \quad \tau_{Ag,w} = \left|\frac{dx_{Ag}}{dx_w}\right|, \tag{1}$$

where $\tau_{Ag,g} \to \infty$ in the single market scenario (thereby cutting off trade) and $\tau_{Ag,w} \to \infty$ in the single and distinct market scenarios.

The trade ratios have an important role in determining relative permit prices, which in a permit market equilibrium are (see, e.g., Malik et al. 1993; Horan and Shortle 2005; Reeling et al. 2018):

$$\tau_{Aw,w} = \frac{v_w}{v_{Aw}}, \quad \tau_{Ag,g} = \frac{v_g}{v_{Ag}}, \quad \tau_{Ag,w} = \frac{v_w}{v_{Ag}}. \tag{2}$$

The final trade ratio is only applicable in an integrated market where nonpoint sources only trade with point sources of nutrients; otherwise there is no case where this ratio is used and so we treat it as effectively being infinite.[4] Condition (2) means that, in distinct markets, prices v_{Aw} and v_{Ag} can be written in terms of the numeraire prices v_w and v_g, respectively, with v_w being the only endogenous price to determine. A single, endogenously-determined numeraire price, v_w, arises in a single market or in an integrated market where nonpoint sources only trade with point sources of nutrients.

The trade ratios also have an important role in determining the market-clearing conditions. Given that prices in the carbon exchange are exogenously determined, only the following market-clearing condition is required for each of the market scenarios:

$$N_w\theta_w x_w = \left(\frac{1}{\tau_{Aw,w}}\right) N_A\theta_{Aw}x_{Aw} + \left(\frac{1}{\tau_{Ag,w}}\right) N_A\theta_{Ag}x_{Ag}, \tag{3}$$

where $\theta_{im} \in [0,1]$ is the proportion of type-*i* firms that trade in market *m*.

---

[4] We demonstrate below that, even with a finite $\tau_{Ag,w}$, an integrated market scenario in which nonpoint sources trade both pollutants with point sources and also participate in the commodity market does not arise in equilibrium.

The proportion θ_{im} may be within the unit interval due to a combination of fixed transactions costs of trading and adverse price effects for type-i firms as θ_{im} increases. Moreover, although an integrated market allows sources to buy or sell both types of pollutants, transactions costs may result in an integrated market being less than integrated (in contrast to Reeling et al. 2018). This is because transactions costs, described below, vary depending on whether the source is buying or selling nutrients, GHGs, or both. Several types of sector-specific outcomes are possible in an integrated market setting. First is a "one-market sector" whereby all participating sources within a sector trade for one pollutant but not the other (i.e., a corner solution for the second pollutant). Second is a "segmented sector" whereby some firms in the sector trade one pollutant while others trade the other pollutant. Third is a "partially-integrated sector" in which some firms in the sector trade one pollutant and others trade both types. Finally, a "fully-integrated sector" has all participating sources within a sector trading both pollutants. We show below that point sources operate as a "fully-integrated sector", which is why the single participation rate θ_w is used in equation (3) (and why a single market-clearing condition is needed for integrated markets). The nonpoint sector is more complex and may involve different participation rates for different pollutants.

The Firms' Problems

Firms trade in competitive permit markets and take permit prices as given. Denote $\Pi_A^{z,P_{Aw},P_{Ag}}$ to be profits for a participating nonpoint source. Superscript $z \in \{S, D, I\}$ denotes the market-trading scenario (S = single, D = distinct, I = integrated). Superscript $P_{Am} \in \{0,1\}$ is an indicator variable equal to 1 if the source supplies permits for pollutant m and 0 otherwise. The single market scenario implies $P_{Ag} = 0$. For all other scenarios, P_{Aw} and P_{Ag} may be one for some firms and zero for others. Denote Π_w^{z,P_w} to be profits for a regulated point source, where $P_w \in \{0,1\}$. Only one indicator variable applies to point sources since they generate a single pollutant e_w and their permit holdings, even under an integrated market, are denominated in terms of this pollutant.

Point and nonpoint sources can use their allocated permits to generate profits of $\Pi_w^{z,0} = \pi_w(0)$ and $\Pi_A^{z,0,0} = \pi_A(0,0)$, respectively, or they can participate in one or more permit markets. The generalized profit relations (assuming credit stacking is allowed) are[5]

(4a) $$\Pi_A^{z,P_{Aw},P_{Ag}} = \pi_A\left(x_{Aw}, x_{Ag}\right) + P_{Aw}v_{Aw}x_{Aw} + P_{Ag}v_{Ag}x_{Ag} - TC_A^{z,P_{Aw},P_{Ag}},$$

(4b) $$\Pi_w^{z,P_w} = \pi_w(x_w) - P_w[v_w x_w + TC_w^{z,1}],$$

where $TC_A^{z,P_{Aw},P_{Ag}}$ and $TC_w^{z,1}$ represent trade-related transactions costs. Transactions costs involve contracting costs (e.g., legal costs, costs of determining a way to measure compliance with the transaction) from setting up bilateral trades and therefore depend on the number of trading partners.[6] Point source transactions costs also include the cost of searching for trade partners and thereby depend on supply and demand. Only point sources incur search costs since they are the ones who are initially regulated and therefore have incentives to find trading partners. We now turn to each source's market decisions, starting with nonpoint sources.

[5] Credit stacking in distinct markets or an integrated market means the nonpoint source can sell permits generated from abatement of each pollutant, even if these permits are generated from the same activity (Robertson et al. 2014). A restriction on credit stacking means a firm can only supply permits for pollutants g or w, but not both.
[6] Transactions costs may also include perceived costs—especially in the case of nonpoint sources who have been hesitant to participate in point-nonpoint markets. For instance, nonpoint sources might perceive that participation may lead to future regulation rather than voluntary participation (King and Kuch 2003; King 2005; Ribaudo and Nickerson 2009).

Nonpoint Sources

We begin by specifying nonpoint transactions costs so that the nonpoint profit relation (4a) is fully specified. Each nonpoint source incurs a fixed contracting cost for each trading partner. The GHG market involves a single partner (the commodity exchange). We also assume a participating nonpoint source trades with a single point source in the nutrient market. This is because an individual unregulated point source tends to generate sizable emissions relative to an individual nonpoint source (although, in aggregate, nonpoint emissions may be greater; Kaufman et al. 2014), implying that a point source's demand exceeds the effective supply from an individual nonpoint source. These assumptions mean a participating nonpoint source's transactions costs are fixed in each scenario, which means these costs only affect participation decisions. We provide more details of the transactions costs below when we examine participation. First we examine permit supply and demand choices for participating firms.

The first-order condition for a nonpoint source's type-m permit supply is

(5) $$\frac{\partial \Pi_A^{z,P_{Aw},P_{Ag}}}{\partial x_{Am}} = 0 \Longrightarrow -\frac{\partial \pi_A(x_{Aw}, x_{Ag})}{\partial x_{Am}} = P_{Am} v_{Am}, m \in \{w, g\}.$$

Condition (5) indicates that each nonpoint source supplying permits for pollutant m equates the marginal costs of supply with the permit price; non-participating sources set marginal profits from emitting equal to zero. After application of condition (2), condition (5) can be solved for an individual nonpoint source's supply $x_{Am}(\mathbf{v}, \boldsymbol{\tau})$ as a function of the numeraire price vector $\mathbf{v} = [v_g \; v_w]$ and the trade ratio vector $\boldsymbol{\tau} = [\tau_{Aw,w} \; \tau_{Ag,g} \; \tau_{Ag,w}]$.[7] The supply relation yields $\partial x_{Am}/\partial v_m > 0$ for $P_{Am} = 1$ and $\partial x_{Am}/\partial v_m = 0$ otherwise. Although

[7] Nonpoint supply also depends on z (since the relevant trade ratios depend on z), P_{Aw}, and P_{Ag}; likewise, point source demand depends on z and P_w. We suppress these arguments in the supply and demand relations for notational convenience and because the scenarios and participation decisions are otherwise indicated.

v_g is fixed when nonpoint sources trade in the carbon exchange, the relation $\partial x_{Am}/\partial v_g > 0$ implies a source's supply of x_{Am} increases when the source enters the GHG market (as prior to entry v_g is essentially treated as equal to zero). This means participation in the GHG market increases firm-level supply in the nutrient market.

Now consider nonpoint source participation decisions. Given the supply responses $x_{Am}(\mathbf{v}, \boldsymbol{\tau})$ and taking prices and trade ratios as given (along with our assumptions about the carbon market), participation decisions for scenario z solve the associated discrete optimization problem:

$$(6) \quad \max_{P_{Aw}}\{\Pi_A^{S,0,0}, \Pi_A^{S,1,0}\}, \max_{P_{Aw},P_{Ag}}\{\Pi_A^{D,0,0}, \Pi_A^{D,1,0}, \Pi_A^{I,0,1}, \Pi_A^{D,1,1}\}, \max_{P_{Aw},P_{Ag}}\{\Pi_A^{I,0,0}, \Pi_A^{I,1,0}, \Pi_A^{I,0,1}, \Pi_A^{I,1,1}\}.$$

The solution to problem (6) depends on fixed transactions costs. We now specify transactions costs in greater detail so that we can better examine participation decisions.

Nonpoint sources that trade a single pollutant with a single partner incur a fixed contracting cost of $TC_A^{z,1,0} = TC_A^{z,0,1} = \kappa_A \; \forall z$. Since a monitoring approach for one type of nonpoint emission may facilitate monitoring the other emission, the total fixed cost of trading with a partner in both markets is $TC_A^{z,1,1} = \psi\kappa_A$ for $z \in \{D, I\}$, where $\psi \in [1,2)$. Note that nonpoint sources operating in an integrated market may only trade with a single point source in the nutrient market. In this case, $TC_A^{I,1,1} = \kappa_A$ since contracting only involves a single partner.

We make three assumptions about κ_A and ψ to avoid trivial or degenerate solutions. First, due to the fixed price of carbon on the exchange, we assume κ_A is large enough that $\Pi_A^{D,0,1} = \Pi_A^{I,0,1} < 0$. Otherwise, there would always be 100 percent nonpoint source participation in the carbon market under scenarios D and I. Second, we assume the initial entrant into the nutrient market earns enough to cover the fixed costs of participation—either by participating in the nutrient market alone or in both markets, i.e., $\Pi_A^{z,1,0}, \Pi_A^{z,1,1} > 0$ for the initial entrant. This ensures trading is at least a possibility in the various scenarios, although whether a market actually emerges also depends on whether point sources participate. Third, we assume nonpoint sources would be willing to trade in the carbon market under any scenario for ψ sufficiently less than 2; this ensures scenario z = D does not degenerate into scenario z = S in cases where nonpoint entry reduces revenue by driving down nutrient permit prices.

Conditions (5) and (6) along with the corresponding point source conditions and market-clearing condition (3) (to determine permit prices) determine nonpoint supplies and participation levels. Although nonpoint firms are homogenous, it is conceivable that price effects could limit entry into one or more markets. For instance, only some firms may participate in the single-market scenario, as greater participation may reduce permit prices until firms are indifferent between participating or not, i.e., $\Pi_A^{S,0,0} = \Pi_A^{S,1,0}$ in equilibrium.

In the case of distinct markets (z = D), our assumptions about κ_A and ψ make it possible that a firm could operate only in the nutrient market or in both markets, but rule out the possibility that some firms may operate only in the carbon market. We can also rule out the possibility that some firms only operate in the nutrient market. For any given set of permit prices, firms that operate in both markets will generate more profits than firms operating only in the nutrient market for two reasons. First, a firm operating in both markets has a profit advantage due to abatement complementarities: the marginal benefit of abating nutrients is greater for firms operating in both markets. Second, the average per-market contracting cost is smaller for a nonpoint source that participates in both markets.

These features imply that all participating nonpoint sources behave identically and are willing to operate jointly in both markets ($\theta_{Aw} = \theta_{Ag} > 0$).

The likelihood of nonpoint sources supplying permits from both pollutants increases in the integrated market case. This is because any nonpoint source willing to sell nutrient permits will also be willing to sell carbon permits to the same point source, i.e.,

(7a) $$\Pi_A^{I,1,1}\big|_{x_{Ag}\text{ sold to PS}} > \Pi_A^{I,1,0}.$$

Indeed, a firm selling nutrient abatement will also generate carbon abatement due to complementarities, and selling this abatement—and likely more—to the same point source does not yield additional transactions costs. Also, for a given set of prices, a participating nonpoint source will opt out of the carbon exchange and instead trade both pollutants with a single point source due to the smaller transactions costs of this strategy, i.e.,

(7b) $$\Pi_A^{I,1,1}\big|_{x_{Ag}\text{ sold to PS}} > \Pi_A^{I,1,1}\big|_{x_{Ag}\text{ sold on exchange}}.$$

The results in (7) imply all nonpoint sources that participate in the integrated market sell both types of permits to point sources such that $\theta_{Ag} = \theta_{Aw}$.

Our results on participation strategies mean the optimization problems in condition (6) become

(8) $$\max\{\Pi_A^z, \Pi_A^0\},$$

where $\Pi_A^0 = \Pi_A^{z,0,0}$, $\Pi_A^S = \Pi_A^{S,1,0}$, $\Pi_A^D = \Pi_A^{D,1,1}$, and $\Pi_A^I = \Pi_A^{I,1,1}$. Whether an interior solution $\theta_{Aw} \in (0,1)$ or a corner solution $\theta_{Aw} \in \{0,1\}$ solves (8) depends on equilibrium prices, described below. Note that a source that participates in market *m* but not market *j* will still choose $x_{Aj} > 0$ due to abatement complementarities, although these credits go unsold.

Point Sources

We now specify point source search and contracting costs so that the point source profit relation (4b) is fully specified. Search costs take the form $\sigma y + F$, where σ is the unit cost of search effort, y, and F is the fixed cost of setting up a search. Variable y is the search effort required to locate enough trading partners to satisfy firm-level demand x_w. The number of partners is x_w divided by the effective firm-level supply (i.e., firm-level supply denominated in the same units as the point source pollutant). The number of partners, denoted Y^z for trade scenario z, is $Y^D = Y^S = \frac{x_w}{x_{Aw}/\tau_{Aw,w}} > 1$ in a single or distinct market and $Y^I = \frac{x_w}{x_{Aw}/\tau_{Aw,w} + x_{Ag}/\tau_{Ag,w}} > 1$ in an integrated market. More generally, we write $Y^z(\mathbf{x}, \boldsymbol{\tau})$, where $\mathbf{x}$ is the vector of demand and supply variables.

Suppose y has been scaled to represent the rate of contacting nonpoint sources. Given that θ_{Aw} represents the proportion of contacts with willing nonpoint participants, the point source's total number of contacts with willing participants is $y\theta_{Aw}$. Setting this contact function equal to the required number of partners, $y\theta_{Aw} = Y^z(\cdot)$, yields $y = Y^z(\cdot)/\theta_{Aw}$. Search costs are then $\sigma(Y^z(\cdot)/\theta_{Aw}) + F$. The contracting cost for a participating point source is $\kappa_w Y^z(\cdot)$, which is the average number of point source trading partners times the per-partner contracting cost κ_w.

Given both search and contracting costs, point source transactions costs are

$$TC_w^{z,1}(\mathbf{x}, \boldsymbol{\tau}, \theta_{Aw}) = Y^z(\mathbf{x}, \boldsymbol{\tau}) \left[\frac{\sigma}{\theta_{Aw}} + \kappa_w\right] + F. \quad (9)$$

Relation (9) indicates a greater demand for credits increases transactions costs since $\partial Y^z(\cdot)/\partial x_w > 0$. Greater nonpoint supplies reduce the required number of trading partners and hence transactions costs since $\partial Y^z(\cdot)/\partial x_{Am} < 0$. This latter effect is amplified in the integrated market scenario so that, all else equal, $TC_w^{I,1}(\cdot) < TC_w^{S,1}(\cdot) = TC_w^{D,1}(\cdot)$. Finally, $\partial TC_w^{z,1}(\cdot)/\partial \tau_{Am,w} > 0$ as a larger ratio means a point source must buy more credits to achieve the same emissions offset, thereby requiring more partners.

A participating point source takes nonpoint abatement supplies as given when choosing x_w, but recognizes that its demand affects its transactions costs by impacting how many trade partners it requires. Accordingly, variable point source transactions costs affect permit demand, whereas the fixed costs may affect point source participation. Our specification for transactions costs differs from Stavins' (1995) and Montero's (1997) approach, as they model transactions costs as potentially increasing functions of the number of traded permits rather than the number of trading partners.

The first-order condition for a point source's demand of nutrient permits is

$$\frac{\partial \Pi_w^{z,P_w}}{\partial x_w} = \pi_w'(x_w) - P_w\left[v_w + \frac{\partial TC^{z,1}(\cdot)}{\partial x_w}\right] = 0. \tag{10}$$

Condition (10) indicates each participating point source optimally equates the marginal profits from emitting with the marginal cost of emitting, where the marginal cost is the permit price and the marginal effects of demand on contracting and search costs. Non-participating sources set marginal profits from emitting equal to zero.

Condition (10) can be solved for an individual point source's demand $x_w(v_w, x_{Aw}(\mathbf{v},\boldsymbol{\tau}), x_{Ag}(\mathbf{v},\boldsymbol{\tau}), \theta_{Aw}, \boldsymbol{\tau})$, where the supply responses $x_{Am}(\mathbf{v},\boldsymbol{\tau})$ generate a strategic effect not found in prior models of permit markets. Demand is increasing in nonpoint supplies (which are increasing in θ_{Aw} and decreasing in the trade ratios), consistent with the impact of these variables on transactions costs. Accordingly, the total demand response to changes in v_w is (recall v_g is fixed, at least when nonpoint sources trade in the carbon exchange)

$$\frac{dx_w}{dv_w} = \frac{\partial x_w}{\partial v_w} + \left(\frac{\partial x_w}{\partial x_{Aw}}\frac{\partial x_{Aw}}{\partial v_w} + \frac{\partial x_w}{\partial x_{Ag}}\frac{\partial x_{Ag}}{\partial v_w}\right).$$

The first RHS term is the direct effect, which is negative and is the traditional demand response holding supply fixed. The term in parentheses represents the strategic effect of a price change due to the supply response. This strategic effect is positive since nonpoint sources supply more for a larger price, thereby reducing search costs. The net effect is ambiguous in sign: $dx_w/dv_w < 0$ ($dx_w/dv_w > 0$) if the direct effect dominates (is dominated by) the strategic effect. It seems reasonable that the direct effect would dominate, and so we assume this is the case.

Now consider point source participation decisions. Given the demand relation $x_w(\cdot)$ and taking prices and trade ratios as given (along with our assumptions about the carbon market), participation decisions for scenario z solve the discrete optimization problem

(11) $$\max\{\Pi_w^0, \Pi_w^z\},$$

where $\Pi_w^0 = \Pi_w^{z,0}$ and $\Pi_w^z = \Pi_w^{z,1}$. Whether an interior solution or a corner solution solves (11) depends on equilibrium prices. We now turn to the market equilibrium.

Market Equilibrium and Stability

The discrete nature of the participation optimization problems (8) and (11) means that, computationally, it is simpler to first solve the market-clearing condition in the nutrient market to obtain equilibrium prices as functions of the participation levels, $\mathbf{v}(\boldsymbol{\theta}, \boldsymbol{\tau})$, where $\boldsymbol{\theta} = [\theta_w \; \theta_{Aw}]$. Specifically, $\mathbf{v}(\boldsymbol{\theta}, \boldsymbol{\tau})$ is determined by solving market condition (3) for scenario z after substituting in the optimized supplies $x_{Am}(\cdot)$ and optimized demand, $x_w(\cdot)$.

Then (8) and (11) can be solved, taking $\mathbf{v}(\boldsymbol{\theta}, \boldsymbol{\tau})$ as given. As indicated above, several interior and corner solutions may arise as potential equilibria. In particular, the number and stability of potential equilibria depend on how profits respond to $\boldsymbol{\theta}$ and in particular on strategic effects impacting this response (Vives 2005).

The stability of potential equilibria is commonly examined by modeling a pseudo-dynamic adjustment or *tâtonnement* process (e.g., Dixit 1986 and Krugman 1991). We model adjustment using replicator dynamics, a mainstay of evolutionary game theory (Rice 2004). Specifically, the proportional change in participation by type-*i* firms, $\dot{\theta}_{iw}/\theta_{iw}$ is proportional to the difference in an individual firm's profits from participating, Π_i^z, and the average profits among all type-*i* firms, $\theta_{iw}\Pi_i^z(\boldsymbol{\theta}, \boldsymbol{\tau}) + (1 - \theta_{iw})\Pi_i^0$, which yields

$$\dot{\theta}_{iw} = \theta_{iw}(1 - \theta_{iw})[\Pi_i^z(\boldsymbol{\theta}, \boldsymbol{\tau}) - \Pi_i^0]. \quad (12)$$

Equation (12) implies the three potential equilibria indicated above for each source: indifference, $\Pi_i^z(\boldsymbol{\theta}, \boldsymbol{\tau}) = \Pi_i^0$, and corner solutions with $\theta_{iw} = 0$ or $\theta_{iw} = 1$. The number and stability of potential equilibria depend on the $\dot{\theta}_{Aw} = 0$ and $\dot{\theta}_w = 0$ isoclines, implicitly defined by the indifference relations $\Pi_i^z(\boldsymbol{\theta}, \boldsymbol{\tau}) = \Pi_i^0$.

Analytically comparing the isoclines in $\theta_{Aw} \times \theta_w$ space is complicated; doing so requires solving market equilibrium conditions (2), (3), (5), and (10) simultaneously for each value of θ_{Aw} and θ_w. We therefore develop a numerical simulation model of permit trading that allows for greater insight into participation dynamics.

A Model of Point-Nonpoint Trading in the Susquehanna River Basin

We explore polluters' market participation decisions using a numerical example based on the Pennsylvania portion of the Susquehanna River Basin (SRB). The SRB is the largest drainage basin within the Chesapeake Bay Watershed and contributes nearly 50 percent of the total nitrogen load to the Bay. Most of this nitrogen (70 percent) comes from agricultural sources—especially row-crop and livestock production (Kaufman et al. 2014). Nutrient trading programs have existed in the Pennsylvania portion of the SRB since 2005. Few trades have occurred, although interest in these programs has increased since the imposition of the 2010 Chesapeake Bay Total Maximum Daily Load regulating nutrient loadings to the Bay (Shortle et al. 2012). Agricultural sources in the SRB also release GHGs to the atmosphere in the form of nitrous oxide (N_2O), methane (CH_4), and carbon dioxide (CO_2). There is currently no market for GHG emissions in Pennsylvania. However, emissions are traded under the auspices of the Regional Greenhouse Gas Initiative, which regulates major point sources in several New England and Mid-Atlantic states bordering Pennsylvania. Hence, there is interest in GHG trading in the region. We develop a simulation of SRB nitrogen pollution and GHG emissions trading and then use this model to illustrate the effect of different market scenarios on polluters' participation decisions numerically.

Simulation Model Description and Calibration

Our simulation model is based on Reeling et al.'s (2018) SRB model, with the exception of a GHG emissions sector (which we do not model) and transactions costs (which they did not model). Let an individual source's base profit function (i.e., profits net of permit revenues and transactions costs) be $\pi_i = \pi_i^u - c_i(\mathbf{x}_i)$. The term π_i^u is unregulated profit. As π_i^u is constant, this term affects neither source-level emissions decisions nor participation decisions (since π_i^u cancels out when comparing π_i under various participatory options).[8] We therefore focus only on sources' abatement cost functions, denoted $c_i(\cdot)$. Abatement in our model is defined as $e_w^u - (\hat{e}_w + x_w)$ (which equals x_w for nonpoint sources). This means we can express abatement costs as a function of just x_w since e_w^u and $\hat{e}_w$ are fixed.

Reeling et al. (2018) calibrate aggregate cost functions for the point and nonpoint sectors in the SRB. Given homogenous firms, the firm-level cost function for sector *i* is simply the aggregate cost function for sector *i* divided by N_i. We therefore use Reeling et al.'s (2018) aggregate cost functions to specify the firm-level abatement cost functions (using our equations for abatement):

(13) $$c_w(x_w) = \frac{1}{3}\frac{\phi_w}{N_w^2}[e_w^u - (\hat{e}_w + x_w)]^3,$$

$$c_A(\mathbf{x_A}) = \sum_m \frac{1}{3}\frac{\phi_{Am}}{N_A^2}[e_{Am}^u - (\hat{e}_{Am} + x_{Am})]^3 - \frac{\gamma}{N^A}[e_{Ag}^u - (\hat{e}_{Ag} + x_{Ag})][e_{Aw}^u - (\hat{e}_{Aw} + x_{Aw})],$$

where the terms in brackets represent firm-level abatement. Multiplying these cost equations by N_w and N_A, respectively, yields the aggregate cost functions in Reeling et al. (2018). Parameters ϕ_{im} and γ are aggregate cost parameters calibrated by Reeling et al. (2018) given that GHGs are measured in million mtCO_2e (metric tons of CO_2 equivalent) and nutrients are measured in 1,000 mtN (metric tons of nitrogen).

Now consider the transactions cost parameters. These are calibrated based on a hypothetical equilibrium outcome that ensures the existence of situations where at least some sources are willing to trade. First, we set the nutrient permit cap, $\hat{e} = \hat{e}_{Aw} + \hat{e}_w$, equal to 113,200 mtN. This is 15 percent larger than the efficient cap Reeling et al. (2018) calculated for the SRB (albeit in the absence of transactions costs) and is consistent with

[8] For agricultural sources operating in competitive markets, the opportunity cost of land likely dissipates profits so that $\pi_A^u = 0$ and aggregate profits in the case of trading are simply the net gains from trade.

the notion that environmental regulators commonly set permit caps exogenously and too lax (Muller and Mendelsohn 2009). Next, we assume an equilibrium in which point and nonpoint sources are each indifferent about participating in a single nutrient market with a trade ratio of $\tau_{Aw,w} = 2$ (the proposed ratio for the SRB and one that is typical of point-nonpoint markets; e.g., Greenhalgh and Selman 2012; Shortle et al. 2012) when $\theta_w = 0.4$, $\theta_{Aw} = 0.3$, and each point source purchases enough credits to increase its emissions cap by 35 percent. These assumptions along with firms' first order conditions (5) and (10), market clearing condition (3), and the indifference relations (12) with $\dot{\theta}_{iw} = 0$ allow us to calibrate $\kappa_A = 18{,}961.5$, variable transactions costs of 1.43×10^6, and $F = 2.24 \times 10^6$. We then assume 30 percent of variable transactions costs stem from search and the remainder from contracting costs, yielding $\kappa_w = 32{,}803$ and $\sigma = 4{,}217.6$. Finally, we assume the price of GHG permits in the emissions exchange is $v_g = 36$, which equals the estimated social cost of carbon (US EPA 2016). In the distinct market scenario, the agricultural source can supply permits to the emissions market at a one-to-one rate such that $\tau_{Ag,g} = 1$.

Market Structure and Equilibrium Participation Dynamics

We begin our numerical analysis by examining point-nonpoint trading in a single nutrient market with fixed point source transactions costs $TC_w^{z,1}$, irrespective of supply, demand, or nonpoint source participation. Specifically, we set $\sigma = \kappa_w = 0$ and then adjust F to equal the total transactions costs arising at our calibrated equilibrium. This special case of the model, which is consistent with some traditional models incorporating transactions costs, removes strategic effects and therefore provides a baseline that will later help us understand the role of strategic effects. Entry in this case depends solely on how $\boldsymbol{\theta}$ affects the permit price. Figure 1, drawn in $\theta_{Aw} \times \theta_w$ space, shows the nonpoint and point sources' participation isoclines are both are positively sloped.[9] The direction of the phase arrows is based on how participation affects permit prices and hence profits—a pecuniary complementarity that is expressed mathematically as:

(15) $$\frac{d\Pi_i^z}{d\theta_j} = \frac{\partial \Pi_i^z}{\partial v_w}\frac{\partial v_w}{\partial \theta_j} > 0.$$

[9] That this must always be true can be confirmed analytically. The slope of source *i*'s isocline is determined by taking the total derivative of the source's indifference relation to yield

$$\left.\frac{d\theta_w}{d\theta_{Aw}}\right|_{\Pi_i^z=\Pi_i^0} = -\left.\frac{\partial \Pi_i^z/\partial \theta_{Aw}}{\partial \Pi_i^z/\partial \theta_w}\right|_{\Pi_i^z=\Pi_i^0} = -\left.\frac{\partial v_w/\partial \theta_{Aw}}{\partial v_w/\partial \theta_w}\right|_{\Pi_i^z=\Pi_i^0} > 0,$$

where the second equality arises after applying the envelope theorem. Even though the slopes of the point and nonpoint isoclines take the same form, they are different since they are evaluated along different indifference relations. Accordingly, the relative slopes are analytically ambiguous.

Relation (15) means that participation choices by point and nonpoint sources have

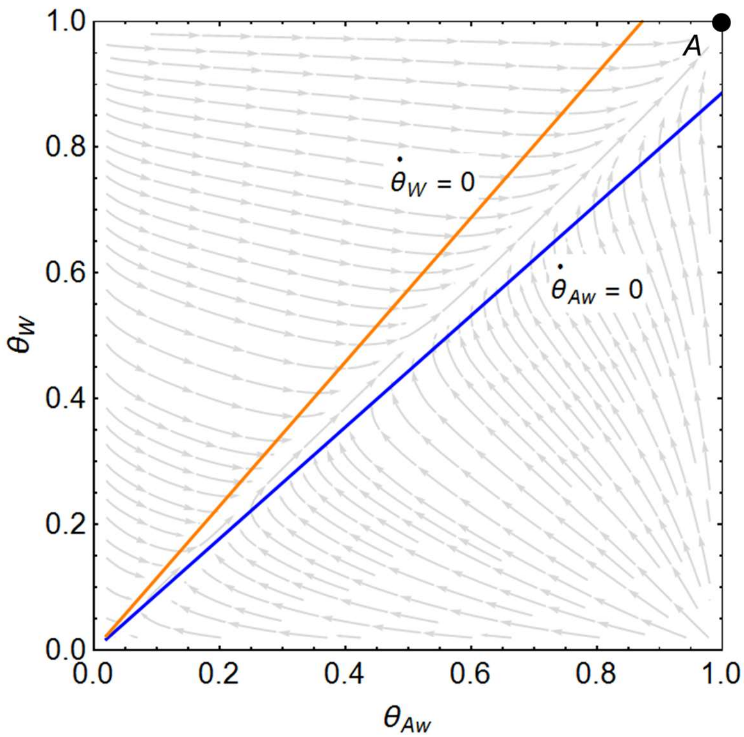


Figure 1. Participation dynamics in a single market with transactions costs and no strategic effects

reinforcing effects. For any given level of θ_{Aw} (i.e., fixing supply), a larger θ_w increases demand to drive up the permit price. This increases nonpoint source profits so that they are positive above the $\dot{\theta}_{Aw} = 0$ isocline. Alternatively, for any given level of θ_w (i.e., fixing demand), a larger θ_{Aw} increases supply to drive down the permit price. This increases point source profits so that they are positive below the $\dot{\theta}_w = 0$ isocline. These price-driven dynamics ensure a globally-stable, full participation equilibrium labeled *A* in figure 1.[10]

Now consider the impact of strategic effects. We continue with the single nutrient market scenario, but we now model point source transactions costs as in (9). Consider the

[10] Both isoclines intersect the origin. Given identical firms, a minimum condition for entry by a particular population in this special case is that the equilibrium permit price arising from trade between one point and one nonpoint source must provide the source with gains that exceed its fixed transactions costs. If this condition is not satisfied, then the source will not have an indifference curve in the positive orthant.

impact of firm-type *j*'s participation θ_{jw} on firm-type *i*'s profits Π_i^S, i.e., $\partial\Pi_i^S/\partial\theta_{jw}$. For nonpoint sources, the derivative $\partial\Pi_A^S/\partial\theta_w$ takes the same form as equation (15). This means there are pecuniary but not strategic effects.

The marginal effect of participation on point source profits is, after applying the envelope theorem,

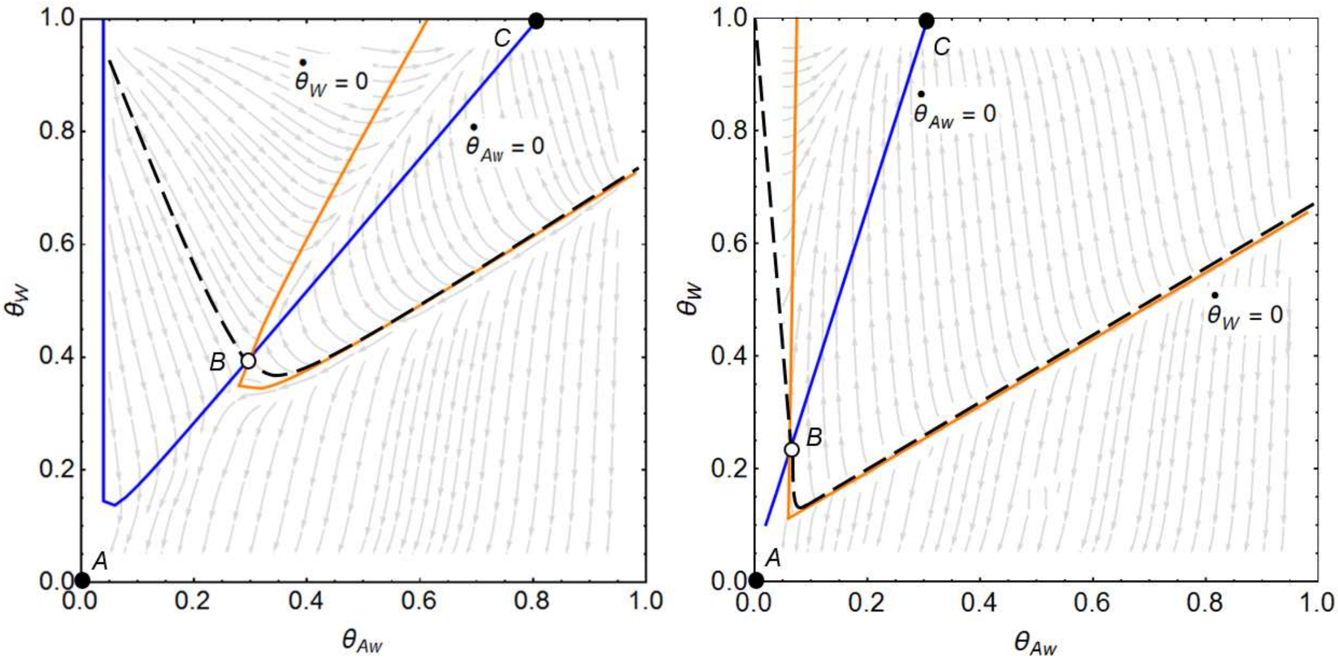
(16) $$\frac{d\Pi_w^S}{d\theta_{Aw}} = \frac{\partial\Pi_w^S}{\partial v_w}\frac{\partial v_w}{\partial\theta_{Aw}} + \frac{\partial\Pi_w^S}{\partial\theta_{Aw}} + \frac{\partial\Pi_w^S}{\partial x_{Aw}}\frac{\partial x_{Aw}}{\partial v_w}\frac{\partial v_w}{\partial\theta_{Aw}}.$$

The first RHS term is the same pecuniary complementarity as is (15). The remaining RHS terms reflect the strategic effects embedded in point source transactions costs. The second RHS term is positive and represents how increased nonpoint source participation directly reduces search costs to increase point source profits. The final RHS term is negative and represents how greater nonpoint source participation indirectly increases point source transactions costs via price effects. Specifically, greater nonpoint participation reduces the permit price, reducing individual permit supplies and hence increasing point source transactions costs to reduce point source profits.

The sign of the RHS of expression (16) is ambiguous due to the ambiguous strategic effects. A positive net strategic effect means a strategic complementarity augments the pecuniary complementarity, increasing the reinforcing effects described for the non-strategic case. A negative net strategic effect means a strategic substitutive effect partially offsets the pecuniary complementarity, reducing the reinforcing effects.

Strategic complementarities may generate multiple equilibria (Vives 2005). The phase plane for this single-market scenario, figure 2, features three equilibria: *A*, *B*, and *C*.

Equilibria *A* and *C* are stable, whereas equilibrium *B* is unstable (a saddle).[11] The dashed line represents the separatrices that divide the basins of attraction for the two stable



a. $\tau_{Aw,w} = 2$

b. $\tau_{Aw,w} = 0.5$

Figure 2. Participation dynamics with transactions costs and strategic effects in a single market

equilibria. The separatrices are essentially an "expectation threshold." The ultimate equilibrium pursued depends on point sources' expectations regarding participation by nonpoint sources and other point sources (only point source expectations are relevant since point sources initiate trades and are the ones facing complementarities).

Suppose point sources expect initial participation levels are above the threshold. Greater nonpoint participation fuels greater point source participation, and vice versa, leading to a thick market that converges at equilibrium *C*. Alternatively, suppose point

---

[11] The saddle point equilibrium *B* is considered unstable since it is associated with the decentralized equilibrium rather than one being managed by a social planner. Note that *B* is the equilibrium we used to calibrate the SRB model, but there was no attempt to influence the stability of *B* via our calibration choices.

sources expect initial participation levels are below the threshold. Less nonpoint participation fuels less point source participation due to increased transactions costs, subsequently reducing price and nonpoint participation so that the system converges at equilibrium A. That is, expectations of a thin market mean the market ultimately fails to form. These results are consistent with the general reluctance of nonpoint sources to participate in pollution markets, and offers a different perspective on Ribaudo and Nickerson's (2009) conclusion that point-nonpoint markets might be more active with greater point source demand.

Figures 2a and 2b differ by the trade ratio $\tau_{Aw,w}$. A larger ratio (figure 2a), as applied in extant point-nonpoint markets, results in a much smaller basin for participation than does a smaller ratio (figure 2b). The reason is that the smaller ratio weakens strategic complementarities by reducing the expected number of trading partners required by each point source. Horan and Shortle (2017) find that smaller trade ratios than those used in practice are likely to be optimal when nonpoint emissions generate risk, and our result here provides another reason for reducing ratios.

Next, we examine how the possibility of multiple equilibria differs by market structure, starting with the distinct market scenario (figure 3). Recall this scenario allows nonpoint sources to participate simultaneously but separately in the nutrient and GHG exchange markets. Also recall that participation in both markets causes nonpoint source transactions costs to increase by the factor $\psi \in [1,2)$ relative to the single-market scenario.

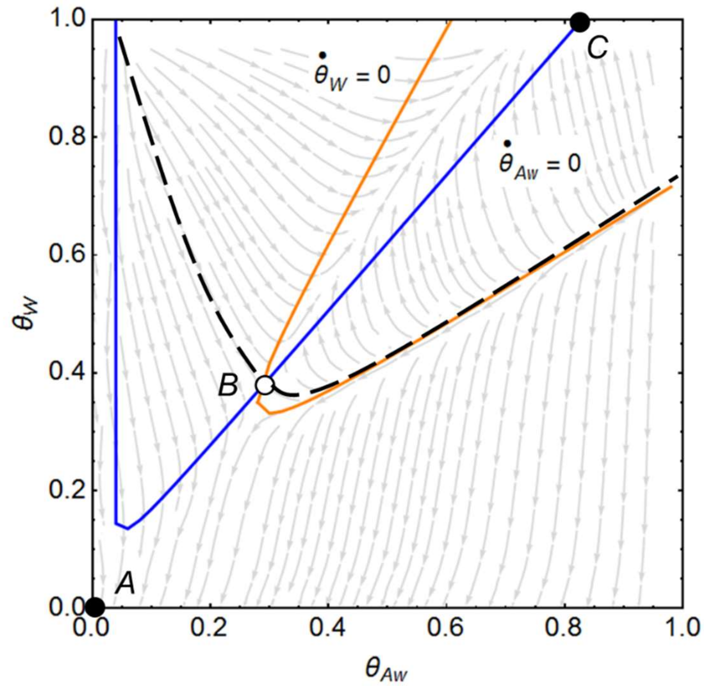


Figure 3. Participation dynamics with transactions costs and strategic effects in distinct markets with ψ = 1

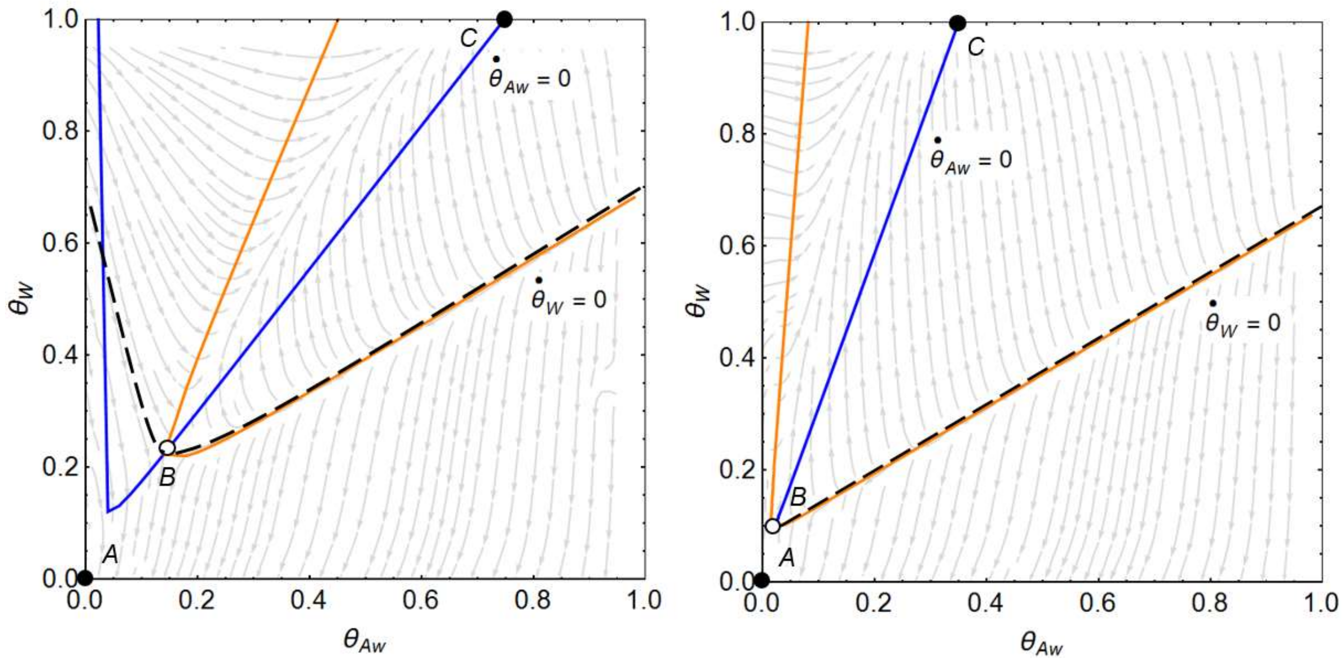
The nonpoint sources' increased GHG abatement in this scenario reduces their marginal costs of nutrient supply due to abatement complementarities. The result is an increase in firm-level nutrient permit supplies. This has nutrient market equilibrium implications for any combination of θ_{Aw} and θ_w and will therefore impact both participation isoclines. Consider the point source isocline. Other things equal, greater firm-level nutrient permit supplies reduce point source transactions costs and also the equilibrium permit price, both of which make point source participation more profitable for any given combination of θ_{Aw} and θ_w. We therefore expect a shift in the $\dot{\theta}_w = 0$ isocline, relative to figure 2, that expands the isosectors where $\dot{\theta}_w > 0$. This expansion occurs in figure 3, but it is very slight. The reason is that the additional market does not alter the strategic complementarity relations arising in (16). Rather, the increase in nonpoint source nutrient supply simply changes the levels at which these complementarities are evaluated, with the effect being small in the neighborhood of the single-market equilibrium.

The overall effect of the GHG market on the $\dot{\theta}_{Aw} = 0$ isocline is ambiguous. Other things equal, the GHG market opportunities along with lower marginal costs of nutrient supply increases the profitability of nonpoint sources who participate in both markets. Assuming transactions costs do not increase when trading in both markets (ψ = 1), profits unambiguously increase for any given combination of θ_{Aw} and θ_w and we expect the $\dot{\theta}_{Aw} = 0$ isocline to shift, relative to figure 2, to expand the isosectors where $\dot{\theta}_{Aw} > 0$. This expansion occurs in figure 3, but it is very slight. This result along with that of the point source isocline suggests that GHG market opportunities have very little impact on nutrient market participation outcomes. We find these results are robust for a large range of marginal GHG abatement costs and abatement cost complementarities.

As the isoclines shift negligibly in the distinct markets case when ψ = 1, even small increases in ψ will shift the $\dot{\theta}_{Aw} = 0$ isocline so that the isosectors where $\dot{\theta}_{Aw} > 0$ are smaller than in figure 2. This means there will be areas of the state space where participating in both markets becomes less profitable than participating in the single nutrient market. Nonpoint sources will choose not to participate in the GHG market in this case—a corner solution that effectively produces the single-market scenario of figure 2.

Finally, consider participation decisions in an integrated market (figure 4). Here, the point source can buy either GHG or water quality permits to meet its emissions cap. All else equal, this means that each nonpoint source's effective supply of permits to point sources is greater, which means the point source can search for and contract with fewer trading partners. This decreases point sources' transactions costs, making point source participation more profitable for any given combination of θ_{Aw} and θ_w. Graphically, the $\dot{\theta}_w = 0$ isocline shifts southwest, relative to figure 2, expanding the isosectors where $\dot{\theta}_w > 0$ along with the basin of attraction for a trading equilibrium. The reason is that inter-pollutant trading reduces strategic complementarities by reducing a point source's number of required trading partners and therefore the reliance on nonpoint source participation decisions. The degree to which the complementarities are reduced varies with $1/\tau_{Ag,w}$, so that a smaller ratio implies smaller complementarities and a larger basin of attraction for the trading equilibrium.

These results are illustrated in figure 4. Figure 4a presents the case where



a. $\tau_{Ag,w} = 0.084$

b. $\tau_{Ag,w} = 0.01$

Figure 4. Participation dynamics with transactions costs and strategic effects in distinct markets

$\tau_{Ag,w}$ =0.084, which is the optimal inter-pollutant trade ratio when there are no transactions costs (as derived from Reeling et al.'s model upon setting $\tau_{Aw,w} = 2$ and removing their industrial emissions sector). Relative to figures 2 and 3, there is a significant shift in the $\dot{\theta}_w = 0$ isocline and a large increase in the basin of attraction for the trading equilibrium *C*. Note that equilibrium *C* involves roughly ten percent less participation by nonpoint sources since the GHG credits allow point sources to meet their regulatory requirements with fewer partners. Figure 4b presents the case where $\tau_{Ag,w} =$ 0.01. Here again the market is much more likely to emerge, with less nonpoint participation required.

Discussion and Conclusion

Thin markets and transactions costs are frequently cited as obstacles to the formation of water quality trading markets (e.g., Woodward et al. 2002; Ribaudo and Nickerson 2009; Wainger and Shortle 2013). We demonstrate that thin markets may arise due to strategic complementarities driven by transactions costs that vary with the level of market

participation by permit suppliers. Strategic complementarities may lead to multiple equilibria characterized by either large or small (or non-existent) levels of trading activity. Specifically, we derive a model of permit trading under a bilateral exchange, typical of many extant nutrient markets in the U.S. Permit buyers' transactions costs in these markets comprise the cost of searching for and contracting with permit suppliers, as well as a fixed costs of setting up a search. Thin markets with few potential trading partners means those who participate in the market may incur greater transactions costs—and earn less profit—than those who do not. This in turn induces even thinner markets. The opposite is true for thick markets. Whether the market develops or not ultimately depends on participants' expectations about the number of trading partners. To our knowledge, this is the first article to illustrate these results analytically and numerically.

We also explore the effect of different market structures on market performance. In particular, we show that allowing permit suppliers to participate in distinct markets for every complementary pollutant they abate may not meaningfully affect trading outcomes relative to the single-market case, at least when trade ratios are not adjusted. This affect arises from greater transactions costs to permit suppliers participating in multiple markets; these costs lower suppliers' profits and, hence, their incentives to participate in both markets. These added transactions costs may be offset by altering trade ratios to change effective permit supplies.

Our results on distinct markets are important given that there is currently considerable interest in the related idea of credit stacking, or allowing permit suppliers to collect revenues for the abatement of every pollutant they generate, even if this abatement arises from the same activity (e.g., Fox et al. 2011; Robertson et al. 2014). Woodward (2011) and others (e.g., Horan et al. 2004) argue for credit stacking on the grounds that it can improve the efficiency of environmental management. However, previous work does not examine the effects of stacking, under different market structures, on participation decisions. We find integrated markets may be more likely to develop and may therefore increase the efficiency of environmental management. These findings extend the results from Reeling et al. (2018), who also find that integrated markets can be more efficient than distinct markets when permit caps are not optimal. But, as with Reeling et al. (2018), any efficiency increases in the present context will depend on policy choices like trade ratios and also the stringency of permit levels. Additional work is needed to explore policy-design in the context of participation decisions.

References

Ambec, S. and J. Coria. 2018. "Policy spillovers in the regulation of multiple pollutants." *Journal of Environmental Economics and Management* 87:114–134.

Cohen, A. and D.A. Keiser. 2017. "The Effectiveness of Incomplete and Overlapping Pollution Regulation: Evidence from Bans on Phosphate in Automatic Dishwasher Detergent." *Journal of Public Economics* 150:53–74.

Dixit, A. 1986. “Comparative Statics for Oligopoly.” *International Economic Review*: 107–122.

Fisher-Vanden, K. and S. Olmstead. 2013. “Moving Pollution Trading from Air to Water: Potential, Problems, and Prognosis.” *Journal of Economic Perspectives* 27(1):147–171.

Fox, J., R.C. Gardner, and T. Maki. 2011. “Stacking Opportunities and Risks in Environmental Credit Markets.” *Environmental Law Reporter* 41:10121–10125.

Greenhalgh, S. and M. Selman. 2012. “Comparing Water Quality Trading Programs: What Lessons are there to Learn?” *The Journal of Regional Analysis & Policy* 42(2):104–125.

Horan, R.D., J.S. Shortle, and D.G. Abler. 2004. “The Coordination and Design of Point-Nonpoint Trading Programs and Agri-Environmental Policies.” *Agricultural and Resouroce Economics Review* 33(1):61–78.

Horan, R.D. and J.S. Shortle. 2005. “When Two Wrongs Make a Right: Second-Best Point-Nonpoint Trading Ratios.” *American Journal of Agricultural Economics* 87:340–352.

———. 2017. “Endogenous Risk and Point-Nonpoint Uncertainty Trading Ratios.” *American Journal of Agricultural Economics* 99(2):427–446.

Kaufman, Z., D. Abler, J. Shortle, J. Harper, J. Hamlett, and P. Feather. 2014. “Agricultural Costs of the Chesapeake Bay Total Maximum Daily Load.” *Environmental Science & Technology* 48:14131–14138.

King, D.M. 2005. “Crunch Time for Water Quality Trading.” *Choices* 20(1):71–75.

King, D.M. and P.J. Kuch. 2003. “Will Nutrient Credit Trading Ever Work? An Assessment of Supply and Demand Problems and Institutional Obstacles.” *Environmental Law*

Reporter News and Analysis 33(5):10352–10368.

Krugman, P.A. 1991. “History versus Expectations.” *The Quarterly Journal of Economics* 106(2):651–667.

Lutter, R. and D. Burtraw. 2002. “Clean Air for Less: Exploiting Tradeoffs Between Different Air Pollutants.” *Fordham Environ Law Journal* 8:555–582.

Malik, A., D. Letson, and S. Crutchfield. 1993. “Point/Nonpoint Source Trading of Pollution Abatement: Choosing the Right Trade Ratio.” *American Journal of Agricultural Economics* 75:959-967.

Montero, J.-P. 1997. “Marketable Pollution Permits with Uncertainty and Transaction Costs.” *Resource and Energy Economics* 20:27–50.

———. 2001. “Multipollutant Markets.” *RAND Journal of Economics* 32:762–774.

Muller, N.Z. and R. Mendelsohn. 2009. “Efficient Pollution Regulation: Getting the Prices Right.” *American Economic Review* 99(5):1714–1793.

Novan, K. 2017. “Overlapping Environmental Policies and the Impact on Pollution.” *Journal of the Association of Environmental and Resource Economists* 4(S1):S153–S199.

Reeling, C., C. Garnache, and R. Horan. 2018. “Efficiency Gains from Integrated Multipollutant Trading.” *Resource and Energy Economics* 52:124–136.

Ribaudo, M.O. and C.J. Nickerson. 2009. “Agriculture and Water Quality Trading: Exploring the Possibilities.” *Journal of Soil and Water Conservation* 64:1–7.

Rice, Sean H. 2004. *Evolutionary theory: mathematical and conceptual foundations*. Sunderland, MA: Sinauer Associates.

Robertson, M., T.K. BenDor, R. Lave, A. Riggsbee, J.B. Ruhl, and M. Doyle. 2014. “Stacking Ecosystem Services.” *Frontiers in Ecology and the Environment* 12(3):186–193.

Shortle, J.S., M. Ribaudo, R.D. Horan, and D. Blandford. 2012. "Reforming Agricultural Nonpoint Pollution Policy in an Increasingly Budget-Constrained Environment." *Environmental Science & Technology* 46(3):1316–1325.

Stavins, R.N. 1995. "Transaction Costs and Tradeable Permits." *Journal of Environmental Economics and Management* 29(2):133–148.8

———. 1998. "What Can We Learn from the Grand Policy Experiment? Lessons from SO_2 Allowance Trading." *Journal of Economic Perspectives* 12(3):69–88.

U.S. Environmental Protection Agency (US EPA). 2016. "Social Cost of Carbon." EPA Fact Sheet. December.

Vitousek, P.M., J.D. Aber, R.W. Howarth, G.E. Likens, P.A. Matson, D.W. Schindler, W.H. Schlesinger, and D.G. Tilman. 1997. "Human Alteration of the Global Nitrogen Cycle: Sources and Consequences." *Ecological Applications* 7(3):737–750.

Vives, X. 2005. "Complementarities and Games: New Developments." *Journal of Economic Literature* 43(2):437–479.

Wainger, L.A. and J.S. Shortle. 2013. "Local Innovations in Water Protection Experiments with Economic Incentives." *Choices* 28(3):1–6.

Woodward, R.T. 2011. "Double-Dipping in Environmental Markets." *Journal of Environmental Economics and Management* 61(2):153–169.

Woodward, R.T. and R.A. Kaiser. 2002. "Market Structures for U.S. Water Quality Trading." *Review of Agricultural Economics* 24(2):366–383.

Woodward, R.T., R.A. Kaiser, and A.M.B. Wicks. 2002. "The Structure and Practice of Water Quality Trading Markets." *Journal of the American Water Resources Association* 38(4)