Spillover Effects and Endogenous Risk in Multipollutant Permit Markets

Alexander S. Hopkins
Department of Agricultural, Food, and Resource Economics
Michigan State University, MI, USA

Richard D. Horan
Department of Agricultural, Food, and Resource Economics
Michigan State University, MI, USA

Carson J. Reeling
Department of Agricultural Economics
Purdue University, West Lafayette, IN, USA

Robert S. Shupp
Department of Agricultural, Food, and Resource Economics
Michigan State University, MI, USA

Although pollution programs have historically focused on individual pollutants, it is well known that many problems involve multiple, linked pollutants (US EPA 2011, 2015; NRC 2004). For example, coal-fired power plants jointly produce sulfur dioxide (SO_2), nitrogen oxides (NO_X), and carbon dioxide (CO_2) (Agee et al. 2014; Novan 2016). Similarly, agricultural use of nitrogen fertilizers contributes to global warming via N_2O emissions and to water quality deterioration due to nutrient loadings delivered into local waterways.

Inefficiencies may arise when pollutant linkages are ignored or when linked pollutants are regulated separately. Benefits can arise under comprehensive multipollutant strategies (NRC 2004; Lutter and Burtraw 2002), including multi-media efforts to protect both water and air (Gray and Shadbegian 2015; Aillery et al. 2005). Market-based approaches can serve as an important implementation mechanism for multipollutant management practices, which are considered a key characteristic of next-generation pollution control efforts (CAAAC 2011; NRC 2004). Several extant programs serve as examples, including the U.S. Cross-State Air Pollution Rule, the European Union Emissions Trading System (EU ETS; EC 2013), and regional programs run jointly by the U.S. Environmental Protection Agency (EPA) and the Minnesota Pollution Control Agency (US EPA 2009).

The potential benefits of comprehensive multipollutant strategies have led to calls for expanding markets that traditionally allow intra-pollutant trading (i.e., trades of "like" pollutants) to allow interpollutant trading of imperfectly substitutable pollutants (NRC 2004; CAAAC 2011). Agricultural sectors appear to be an obvious candidate for such trades because agricultural production utilizes numerous chemicals that affect multiple environmental media.

Reeling et al. (2018) explored the efficiency gains from using a multipollutant permit market when permit caps are sub-optimally lax, which is a common concern. Specifically, focusing on a case in which agricultural production generates nitrogen emissions affecting both air and water, they explored the design of markets that allow previously unregulated agricultural sources to participate in air and water quality markets to offset the emissions of point sources. Trades among sources were guided by trade ratios that defined the required reduction in agricultural emissions to offset point source emissions. In this setting, they showed that either distinct markets (i.e., those allowing only intrapollutant trading) or integrated markets (i.e., those allowing both intra- and interpollutant trading) could be first best, provided the total number of permits (the permit cap) for each pollutant was set optimally. The optimal trade ratios in this case equal the ratio of marginal damages associated with the two pollutants being traded, guiding relative permit prices to reflect these external impacts. Once inefficiencies are introduced in the form of sub-optimal permit caps, however, each trade ratio can be utilized to perform multiple tasks in an effort to offset these inefficiencies: they can be used to guide relative prices and also the effective permit caps. These tasks are managed by adding adjustment terms to the second-best ratios to reflect the degree of inefficiencies associated with the nominal caps. In this setting, integrated markets can utilize the interpollutant trade ratio as an additional policy tool to reallocate permits across sectors in ways that reduce the nominal cap inefficiencies.

Reeleing et al.'s analysis made the simplifying assumption that agricultural pollution is deterministic, when in fact it is largely weather driven and therefore highly stochastic. When emissions are stochastic, firms must trade based on mean emissions rather than actual emissions (Shortle 1987; Malik et al. 1993), and this is how point-nonpoint trading operates in practice (USEPA 2011). In such a market, farmers only have incentives to consider the impacts of their input choices on mean emissions; they ignore impacts to higher moments of the distribution, such as the variance, that could have significant impacts on expected damages from pollution. Inefficiencies arise even when the nominal permit cap is chosen optimally.

We examine point-nonpoint trading when agricultural nonpoint sources jointly produce stochastic emissions of multiple pollutants. We find the inefficiencies associated with trading mean emissions may be exacerbated in this setting since choosing inputs to manage the mean of one pollutant will have unintended consequences on the higher moments of all pollutants. In light of these inefficiencies, we again find that an integrated market can be efficiency-enhancing due to the additional policy tool of the interpollutant trade ratio. Its optimal value should equal the ratio of expected marginal damages for the two sectors involved in the trade, plus two risk adjustment terms. The first adjustment term reflects the relative within-sector risks associated with controlling mean emissions within each sector (e.g., altering input use to manage mean water emissions will affect higher moments of water emissions). The second adjustment reflects the relative cross-sector risk effects (e.g., altering input use to manage mean water emissions will affect the distribution of air emissions). These adjustments will optimally reallocate controls across sectors to incentivize more control in the sector having fewer adverse spillover effects. Intra-pollutant trade ratios are also adjusted to account for spillovers, but the qualitative effects are more ambiguous.

We illustrate our theoretical findings numerically via a simulation model of nitrogen oxide air emissions and nitrogen water loadings from agricultural (nonpoint) sources and point sources within the Susquehanna River Basin (SRB) of the Chesapeake Bay watershed. We examine both distinct and integrated markets and find integrated markets perform significantly better under many circumstances. This outcome occurs because the optimal interpollutant ratio reallocates more controls towards the sector responsible for generating greater risks (i.e., more economically relevant stochasticity as manifest through damages), in an effort to reduce those risks. We also find the intra-pollutant trade ratios adjust. For instance, we find the optimal water quality ratio is roughly three times smaller than the values applied in practice.

The Conceptual Model

Consider a region in which an industrial sector (indexed by *I*) produces point source atmospheric emissions of nitrogen oxides, a wastewater sector (indexed by W) produces point source total nitrogen loadings delivered into a local water body, and an agricultural sector (indexed by A) produces nonpoint source pollution of both types. As we will assume competitive permit market, we aggregate among polluters in each sector, treating each sector as an individual decision-maker, and focus on trades across sectors. Air emissions by source $i \in \{I, A\}$ are denoted e_I, and water loadings by source $i \in \{W, A\}$ are denoted r_W. Point source pollution is observable and deterministic so that these sources can control their pollution with certainty according to the continuously differentiable, convex cost functions $c_I(e_I, \gamma_I)$ and $c_W(r_W, \gamma_W)$, where γ_i is a cost parameter. We assume $c_I(0) = c_W(0) = 0$, $dc_I/de_I < 0$, and $dc_W/dr_W < 0$.

Unlike the point sources, the diffuse nature of agricultural pollution makes it unobservable at an acceptable societal cost, and these pollutants are largely weather-driven off farm fields so that this pollution is stochastic. Agricultural air emissions and water loadings are produced according to the functions $e_A(\mathbf{x}, \boldsymbol{\theta})$ and $r_A(\mathbf{x}, \boldsymbol{\theta})$, respectively, where $\mathbf{x} = (x_1, \dots, x_M)$ is a vector representing the sector's input choices (e.g., production choices and pollution control efforts) and $\boldsymbol{\theta} = (\theta_1, \dots, \theta_P)$ is random vector that impacts agricultural pollution (e.g., weather events). The sector's profits are a function of its input use, $\pi(\mathbf{x}, \gamma_A)$. Absent any regulation, the sector will choose the (private) optimal input vector $\mathbf{x}_0 = (x_{10}, \dots, x_{M0})$, earning profits $\pi(\mathbf{x}_0)$. Agricultural pollution control costs are therefore $c_A(\mathbf{x}, \gamma_A) \equiv \pi(\mathbf{x}_0, \gamma_A) - \pi(\mathbf{x}, \gamma_A)$.

The permit market we examine bases nonpoint source permits on mean emissions and mean loadings and so the agricultural source has incentives to control only mean pollution levels. Accordingly, we focus on the following restricted abatement cost functions

$$c_A(\bar{e}_A, \bar{r}_A, \gamma_A) \equiv c_A(\mathbf{x}(\bar{e}_A, \bar{r}_A, \gamma_A), \gamma_A)$$

$$\equiv \min_{\mathbf{x}} c_A(\mathbf{x}, \gamma_A) \quad \text{s.t.} \quad E\{e_A(\mathbf{x}, \boldsymbol{\theta})\} \leq \bar{e}_A \quad \text{and} \quad E\{r_A(\mathbf{x}, \boldsymbol{\theta})\} \leq \bar{r}_A,$$

where $\mathbf{x}(\bar{e}_A, \bar{r}_A, \gamma_A)$ denotes the sector's optimal input usage given the mean pollution targets $\bar{e}_A$ and $\bar{r}_A$, and where E is the expectations operator is taken over the random vector $\boldsymbol{\theta}$. We assume $c_A(\cdot)$ is a continuously differentiable, convex function that is decreasing in both of its arguments. The pollutant levels resulting from the input responses are $e_A(\bar{e}_A, \bar{r}_A, \boldsymbol{\theta}, \gamma_A) \equiv e_A(\mathbf{x}(\bar{e}_A, \bar{r}_A, \gamma_A), \boldsymbol{\theta})$ and $r_A(\bar{e}_A, \bar{r}_A, \boldsymbol{\theta}, \gamma_A) \equiv r_A(\mathbf{x}(\bar{e}_A, \bar{r}_A, \gamma_A), \boldsymbol{\theta})$.

Pollution causes separate economic damages from air emissions, $D_e\big(e_I, e_A(\bar{e}_A, \bar{r}_A, \boldsymbol{\theta}, \gamma_A)\big)$, and water loadings, $D_r\big(r_W, r_A(\bar{e}_A, \bar{r}_A, \boldsymbol{\theta}, \gamma_A)\big)$. Both damage functions are assumed to be twice-continuously differentiable, and increasing and convex in pollution. Note that damages are stochastic due to stochastic nonpoint pollution and that both damage functions depend on mean agricultural air emissions and water loadings. The expected social costs stemming from pollution and its control are given by

$$ESC \equiv E\{c_I(e_I, \gamma_I)\} + E\{c_W(r_W, \gamma_W)\} + E\{c_A(\bar{e}_A, \bar{r}_A, \gamma_A)\}$$

$$+E\big\{D_e\big(e_I, e_A(\bar{e}_A, \bar{r}_A, \boldsymbol{\theta}, \gamma_A)\big)\big\} + E\big\{D_r\big(r_W, r_A(\bar{e}_A, \bar{r}_A, \boldsymbol{\theta}, \gamma_A)\big)\big\}.$$

2. Permit Markets and Multipollutant Trades

Consider a competitive market in which there are separate categories of pollution permits, with each category specific to the pollutant and its source. We write $\hat{e}_I$ and $\hat{r}_W$ to denote the point source permits, denominated in terms of actual air emissions or water loadings, with prices p_{eI} and p_{rW}. Agricultural permits, denominated in terms of mean air emissions and mean water loadings, are denoted $\hat{e}_A$ and $\hat{r}_A$ with prices p_{eA} and p_{rA}. Pre-trade, each sector only holds permits for its sector and pollution type. The initial permit allocations in a market are denoted $\hat{e}_{I0}$, $\hat{r}_{W0}$, $\hat{e}_{A0}$, and $\hat{r}_{A0}$.

Sources in a market can trade for different permits to increase their allowable pollution levels, subject to trade ratios governing how a permit for one pollutant is converted into another. Upon using these trade ratios to convert a polluter's permits into the relevant denomination, the point sources must hold a combination permits at least equal to their air emissions or water loadings, while the nonpoint source must hold a combination of permits at least equal to its expected air emissions and expected water loadings. We consider two market structures: distinct markets, in which intra-pollutant trades (trading like pollutants) but not inter-pollutant or cross-media trades (i.e., trading air emissions for water loadings, and vice versa) are not allowed, and a single, integrated market in which both intra-pollutant and cross-media trades are allowed.[1]

First consider distinct markets, as extant trading programs are of this form. The point source pollutants serve as the numeraire in their respective markets, giving us two intra-pollutant trade ratios: a ratio for air emissions, $\tau_{eA,eI} \equiv |d\hat{e}_A/d\hat{e}_I|$, and a ratio for water loadings, $\tau_{rA,rW} \equiv$

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[1] Note that our framework implicitly assumes that the agricultural sector can "stack credits", i.e., the agricultural sector can simultaneously collect revenue from air emissions permit sales and water loadings permit sales. This observation could prove to be an important caveat to our model, as current trade programs do not allow this "stacking" behavior.

$|d\hat{r}_A/d\hat{r}_W|$. These ratios determine how many air emissions (water loadings) permits the industrial sector (wastewater sector) must purchase from the agricultural sector to increase their air emissions (water loadings) by one unit.

Now consider an integrated market. Letting the industrial pollutant serve as the numeraire in this single market, we define three "primary" trade ratios: an inter-pollutant ratio between sectors I and W, $\tau_{rW,eI} \equiv |d\hat{r}_W/d\hat{e}_I|$; an intra-pollutant ratio between sectors I and A, $\tau_{eA,eI} \equiv |d\hat{e}_A/d\hat{e}_I|$; and an inter-pollutant ratio between sectors I and A, $\tau_{rA,eI} \equiv |d\hat{r}_A/d\hat{e}_I|$. These ratios determine how many permits the industrial sector must buy from another sector to increase its emissions by one unit. Other trades may occur in the market, with terms of trade guided by various combinations of the primary ratios. There are two ratios between sectors W and A: an intra-pollutant ratio, $\tau_{rA,rW} \equiv |d\hat{r}_A/d\hat{r}_W| = \tau_{rA,eI}/\tau_{rW,eI}$, and an inter-pollutant ratio, $\tau_{eA,rW} \equiv |d\hat{e}_A/d\hat{r}_W| = \tau_{eA,eI}/\tau_{rW,eI}$, and an inter-pollutant ratio within the agricultural sector, $\tau_{eA,rA} \equiv |d\hat{e}_A/d\hat{r}_A| = \tau_{eA,eI}/\tau_{rA,eI}$.

In either market framework, the industrial and wastewater sectors will choose their pollution levels and permit holdings to minimize their net total costs, given that their pollution levels cannot exceed their permit holdings. Similarly, the agricultural sector will choose its mean pollution levels and its permit holdings to minimize its net total costs, given that its expected total pollution cannot exceed its permit holdings. In Appendix A, we show that the sectors' cost minimization problems, for each market type, may be written as:

(1a) $\min_{e_I} c_I(e_I) + p_{eI}(e_I - \hat{e}_{I0})$

(1b) $\min_{r_W} c_W(r_W) + p_{rW}(r_W - \hat{r}_{W0})$

(1c) $\min_{\bar{e}_A,\bar{r}_A} c_A(\bar{e}_A,\bar{r}_A) + p_{eA}(\bar{e}_A - \hat{e}_{A0}) + p_{rA}(\bar{r}_A - \hat{r}_{A0})$

Assuming an interior solution, the standard first-order conditions (FOCs) corresponding to the minimization problems in (1) are:

$$\frac{dc_I}{de_I} + p_{eI} = 0 \rightarrow p_{eI} = -\frac{dc_I}{de_I} > 0 \tag{2a}$$

$$\frac{dc_W}{dr_W} + p_{rW} = 0 \rightarrow p_{rW} = -\frac{dc_W}{dr_W} > 0 \tag{2b}$$

$$\frac{\partial c_A}{\partial \bar{e}_A} + p_{eA} = 0 \rightarrow p_{eA} = -\frac{\partial c_A}{\partial \bar{e}_A} > 0 \tag{2c}$$

$$\frac{\partial c_A}{\partial \bar{r}_A} + p_{rA} = 0 \rightarrow p_{rA} = -\frac{\partial c_A}{\partial \bar{r}_A} > 0. \tag{2d}$$

Condition (2) states that, at the optimum, each source's reduction in marginal pollution costs (alternatively, each source's marginal benefits of pollution) must equal the relevant permit price.

We show in Appendix A that the trade ratios equal the ratio of the relevant permit prices in a market equilibrium. This gives us two *market equilibrium* conditions in the distinct market setup and three market equilibrium conditions in the integrated market setup. The conditions in a distinct market are

$$\tau_{eA,eI} = \frac{p_{eI}}{p_{eA}} = \frac{dc_I/de_I}{\partial c_A/\partial \bar{e}_A} \rightarrow p_{eA} = \frac{p_{eI}}{\tau_{eA,eI}} = -\frac{\partial c_A}{\partial \bar{e}_A} \tag{5a}$$

$$\tau_{rA,rW} = \frac{p_{rW}}{p_{rA}} = \frac{dc_W/dr_W}{\partial c_A/\partial \bar{r}_A} \rightarrow p_{rA} = \frac{p_{rW}}{\tau_{rA,rW}} = -\frac{\partial c_A}{\partial \bar{r}_A} \tag{5b}$$

while the conditions in an integrated market are

$$\tau_{rW,eI} = \frac{p_{eI}}{p_{rW}} = \frac{dc_I/de_I}{dc_W/dr_W} \rightarrow p_{rW} = \frac{p_{eI}}{\tau_{rW,eI}} = -\frac{dc_W}{dr_W} \tag{6a}$$

$$\tau_{eA,eI} = \frac{p_{eI}}{p_{eA}} = \frac{dc_{\mathrm{I}}/de_I}{\partial c_A/\partial \bar{e}_A} \rightarrow p_{eA} = \frac{p_{eI}}{\tau_{eA,eI}} = -\frac{\partial c_A}{\partial \bar{e}_A} \tag{6b}$$

$$\tau_{rA,eI} = \frac{p_{eI}}{p_{rA}} = \frac{dc_{\mathrm{I}}/de_I}{\partial c_A/\partial \bar{r}_A} \rightarrow p_{rA} = \frac{p_{eI}}{\tau_{rA,eI}} = -\frac{\partial c_A}{\partial \bar{r}_A}, \tag{6c}$$

where the final equalities in (5) and (6) stem from (1). Accordingly, in distinct markets the firm response functions that solve the FOCs depend on the point source permit price and the relevant trade ratios (if any): $e_I(p_{eI}), r_W(p_{rW})$, and $\bar{k}_A(p_{eI}, p_{rW}, \tau_{eA,eI}, \tau_{rA,rW})$ for $k \in \{e, r\}$. In integrated markets, the firm response functions depend on the point source emissions price and the relevant trade ratio: $e_I(p_{eI}), r_W(p_{eI}, \tau_{rW,eI})$, and $\bar{k}_A(p_{eI}, \tau_{eA,eI}, \tau_{rA,eI})$ for $k \in \{e, r\}$). Notice that the responses under either market structure are independent of the initial permit allocation.

Now consider the market clearing conditions that determine the permit prices. In the case of distinct markets, each market has a single *market clearing condition*:

(7a)
$$\underbrace{\hat{e}_{I0} + \frac{1}{\tau_{eA,eI}}\hat{e}_{A0}}_{Q_e} = e_I + \frac{1}{\tau_{eA,eI}}\bar{e}_A$$

(7b)
$$\underbrace{\hat{r}_{W0} + \frac{1}{\tau_{rA,rW}}\hat{r}_{A0}}_{Q_r} = r_W + \frac{1}{\tau_{rA,rW}}\bar{r}_A,$$

where the left-hand-side (LHS) quantities Q_e and Q_r in (7) are the effective aggregate permit caps in the markets, and where the right-hand-side (RHS) quantities are the expected aggregate air emissions or water loadings in the markets. Equations (7) simply require that, in equilibrium, the amount of expected pollution occurring in the market is equal to the permit holdings in the market, where all quantities are denominated in terms of the relevant point source numeraire. Since firm responses do not depend on the initial allocation, we can simply write the LHS of (7) in terms of the aggregate quantities and use Q_e and Q_r rather than the permit allocations as the choice variables. Condition (7) determines the equilibrium permit prices $p_{eI}(\mathbf{Q}, \boldsymbol{\tau})$ and $p_{rW}(\mathbf{Q}, \boldsymbol{\tau})$, where $\mathbf{Q} = (Q_e, \mathrm{Q_r})$ and $\boldsymbol{\tau} = (\tau_{eA,eI}, \tau_{rA,rW})$. Note that these prices depend on the market variables for both markets since the agricultural sector operates in both markets. Finally, polluter responses can be written solely in terms of the market parameters $\mathbf{Q}$ and $\boldsymbol{\tau}$.

The integrated market has a single market-clearing condition:

(8)
$$\underbrace{\hat{e}_{I0} + \frac{1}{\tau_{rW,eI}}\hat{r}_{W0} + \frac{1}{\tau_{eA,eI}}\hat{e}_{A0} + \frac{1}{\tau_{rA,eI}}\hat{r}_{A0}}_{Q} = e_I + \frac{1}{\tau_{rW,eI}}r_W + \frac{1}{\tau_{eA,eI}}\bar{e}_A + \frac{1}{\tau_{rA,eI}}\bar{r}_A.$$

As in equation (7), the LHS of (8) is the effective aggregate permit cap (Q) while the RHS denotes total pollution levels, with both values denominated in terms of the numeraire. Again, since firm responses do not depend on the initial allocation, we can simply write the LHS of (8) in terms of the aggregate quantities and use Q rather than the permit allocations as the choice variable. Condition (8) determines the equilibrium permit price $p_{eI}(\mathbf{Q}, \boldsymbol{\tau})$, where $\boldsymbol{\tau} = (\tau_{rW,eI}, \tau_{eA,eI}, \tau_{rA,eI})$ and $\mathbf{Q} = Q$ is a scalar in this case. As above, polluter responses can be written solely in terms of the market parameters $\mathbf{Q}$ and $\boldsymbol{\tau}$.

3. The Agency's Problem

Suppose society is risk neutral so that the agency's objective is to minimize expected social costs, subject to the market responses. The policy tools at its disposal are $\mathbf{Q}$ and $\boldsymbol{\tau}$, where the elements of the choice vectors differ by market type as defined above. Formally, the agency's problem is

$$\text{(9)} \quad \min_{\mathbf{Q},\boldsymbol{\tau}} ESC(\mathbf{Q}, \boldsymbol{\tau}) \equiv E\{c_I(e_I(\mathbf{Q}, \boldsymbol{\tau}))\} + E\{c_W(r_W(\mathbf{Q}, \boldsymbol{\tau}))\}$$

$$+E\{D_e[e_I(\mathbf{Q}, \boldsymbol{\tau}), e_A(\bar{e}_A(\mathbf{Q}, \boldsymbol{\tau}), \bar{r}_A(\mathbf{Q}, \boldsymbol{\tau}), \boldsymbol{\theta})]\} + E\{D_r[r_W(\mathbf{Q}, \boldsymbol{\tau}), r_A(\bar{e}_A(\mathbf{Q}, \boldsymbol{\tau}), \bar{r}_A(\mathbf{Q}, \boldsymbol{\tau}), \boldsymbol{\theta})]\}.$$

Note that the permit markets will not be first-best, for two reasons. The first is that the agency has uncertainty about polluters' costs. The second is that agricultural permits are based on mean pollution levels. One results is that agricultural sources are not incentivized to consider the impacts of their choices on higher moments of the distribution of pollution that affect damages (Shortle et al. 1998; Horan et al. 2002). The focus on mean emissions also results in each agricultural pollutant responding to changes in the mean of both agricultural pollutants, resulting in spillover effects across sectors. We therefore refer to the solution to (9) as the second-best market design for a particular market structure. This terminology may oversimplify things a bit, however, as one type of market structure may be more efficient than the other. In a sense, the comparison between market structures might be thought of as one involving prices versus quantities, as the distinct market scenario uses one extra quantity and one fewer price (i.e., trade ratio) than the integrated market. Price and quantity instruments perform differently when there is asymmetric information, but typically not when there is symmetric information (Weitzman 1974). Here, the second-best nature of the problem, with spillover effects across polluting sectors, opens the possibility that these instruments might perform differently even when there is not asymmetric information. Comparing the relative performance of the two instruments is inherently a numerical issue (Horan and Shortle 2021).

Numerical Example

We adapt Reeling et al.'s (2018) model of pollution in the Susquehanna River Basin (SRB) watershed and airshed by point sources and agricultural nonpoint sources. There are three main differences relative to their model. First, we assume the regulator has uncertainty about the marginal abatement cost values used to calibrate the model. Specifically, we assume the regulator assumes these values are uniformly distributed with a mean value as reported in Reeling et al., but with upper and lower bounds that are 33% higher and lower than the mean. This introduces asymmetric information into the model. Second, we assume nonpoint emissions are stochastic and take the following form: $e_A = \varepsilon_e(\bar{e}_A + \alpha_r \bar{r}_A)$ and $r_A = \varepsilon_r(\bar{r}_A + \alpha_e \bar{e}_A)$, where the ε_i terms are random variables such that $\varepsilon_i \sim U(0.67, 1.33)$, and $\alpha_i > 0$ is a parameter reflecting that actual emissions depend on behavioral input use responses that depend on the mean of both pollutants.

Our results at this point are preliminary. We find that both markets perform equivalently when there is no asymmetric information, with expected social costs in each case being \$3.65B (billion). In the case of distinct markets, $Q_e^* = 143.8$ million mtCo2e, $Q_r^* = 32$ thousand mtTN, $\tau_{eA,eI}^* = 1$, and $\tau_{rA,rW}^* = 0.7$. The unitary trade ratio is expected when there is no economic risk (due to linear damages), and the smaller ratio for loadings is consistent with nonpoint loadings being risky (Horan and Shortle 2017). In the case of integrated markets, $Q_e^* = 148.1$ million mtCo2e, $\tau_{eA,eI}^* = 1$, $\tau_{rW,eI}^* = 7.75$, and $\tau_{rA,eI}^* = 5.45$. These results imply $\tau_{rA,rW}^* = 0.7$ and aggregate emissions and loadings at the same levels as in the distinct market case.

The two markets perform identically because the agency has enough flexibility in the choice of pollution caps in the distinct market case. Reeling et al. found that integrated markets performed better when the caps become constrained (since integrated markets have an additional policy tool—the inter-pollutant ratio—once the caps are fixed), as is common in practice since nonpoint source caps are generally set at their unregulated levels whereas point source emissions are generally regulated by authorities outside of the trading program (Horan and Shortle 2017). Our next step will be to investigate the effect of uncertainty in this case; our hypothesis is that stochasticity will exacerbate the relative gains from the integrated markets since those markets provide an additional tool that can help to manage risk.

Now consider the case with asymmetric information in addition to stochastic emissions. Here we find that the integrated market performs better: prices outperform quantities (although the difference is not great—only about $200,000, although again the results are very preliminary). We find that asymmetric information creates the greatest risks in the industrial emissions sector, resulting increased incentives to encourage trades with agricultural sources. The industrial sector experiences greater risks in our analysis because the agency's uncertainty was proportional to (at the same rate) the marginal abatement costs in each sector, and the industrial sector had significantly larger marginal abatement costs—and hence greater uncertainty in our model—than the others. Integrated markets provided an increased opportunity to dealing with this uncertainty by allowing trades across sectors so that wastewater treatment—which had the lowest risks overall, could take on more abatement responsibilities. This result enhances prior results by Reeling et al. (2018).

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