A Laboratory Experiment on Bilateral Oligopoly in Emissions Trading Markets

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1. INTRODUCTION

Market power in emissions trading markets has been extensively investigated because emerging markets for tradable emissions permits such as the European Union's Emissions Trading Scheme (ETS) could be very largely dominated by relatively few big sellers or buyers. Previous studies on market power in emissions trading assume the existence of a subset of competitive players. A key feature of emissions trading markets, however, is that emissions permits are often traded by a limited number of large sellers and buyers. Thus, both sellers and buyers can influence the market price in their favor, and emissions trading markets could be well described by a model of bilateral oligopoly where every trader can exercise market power.

Using a laboratory experiment, our objective in this paper is to test the performance of an emissions trading market utilizing a double auction in bilateral oligopoly. The issue we address regards the robustness of the double auction to the impact of market power on trading (Smith, 1981; Smith and Williams, 1989; Ledyard and Szakaly-Moore, 1994; Godby, 1999; Muller et al., 2002; Cason, Gangadharan and Duke, 2003; Sturm, 2008). We also address the impact of market power on the abatement cost savings achieved by emissions permits trading. In contrast with an experiment literature on market power, a benchmark for the experiment in our study is derived from a framework with 'slope takers', which was originally developed by Weretka (2011a). In the framework with slope takers, all traders are assumed to be endowed with correct beliefs about slopes of their market supplies/demands and they take the slopes of their market supplies/demands as given. Every trader can exercise market power, which is determined endogenously as part of the equilibrium concept. The ability of each trader to affect prices of emissions permits depends on his or her production technology as well as the size and number of traders in the market. In this respect, the framework with slope-takers is less restrictive than such traditional models of imperfect competition assumed in the experiment literature, like monopoly, monopsony, and Cournot, which *a priori* assume that a seller or buyer may have dominating market power. As the number of traders increases, market outcomes predicted by the framework with slope-takers would converge to those in perfect competition.

The analysis of bilateral oligopoly has recently gained increasing attention from the literature on market power. Two models have been applied to the analysis of bilateral oligopoly. First, Hendricks and McAfee (2010) apply a supply function equilibrium model developed by Klemperer and Meyer (1989) to bilateral oligopoly, assuming that each trader selects a supply function from a one-parameter family of nonlinear schedules indexed by its capacity for production or consumption and reports it to auctioneers. Malueg and Yates (2009) also apply the supply function equilibrium model to the analysis of bilateral oligopoly in emissions trading markets. These studies that use a supply function equilibrium model assume the existence of competitive traders, which enables the inverse demand function for strategic firms to be identified. Second, Hortacsu and Puller (2008) apply a share auction model developed by Wilson (1979) to electricity bidding, assuming a stochastic term in aggregated demand and an additively separable class of supply strategies. Wirl (2009) also applies the share auction model to the analysis of bilateral oligopoly in emissions markets. These studies that use a share auction model assume a stochastic term in the aggregate demand function, which enables identification of the optimal supply strategies. The slope-takers framework is more general than these models, as it needs *neither* the existence of competitive traders *nor* a stochastic term in aggregate demand to identify the supply functions of strategic traders. The market power of *all* traders is determined endogenously. The equilibrium results from endowing all traders with consistent beliefs about the slopes of their market's supplies/demands and assuming their profit-maximizing choice of trade in an emissions trading market, given such beliefs.

Section 2 presents a slope-takers framework that describes bilateral oligopoly in an emissions trading market. This section also summarizes hypotheses tested by a laboratory experiment. Section 3 then presents experimental design and results. Section 4 concludes the analysis.

2. THEORETICAL MODEL AND RESEARCH QUESTIONS

2.1. The Model

Consider an emissions trading market where *all* firms with the initial endowment of emissions allowances can affect the price of permits, denoted by p. Let q_i denote the net sales of permits of firm i. Then, firm i's ability to affect the price is represented by the price impact, which is defined as $-\partial p/\partial q_i$. Prior to emissions trading, firms have made production commitments so that both product price and quantity are fixed. Given the initial endowment of allowances and abatement technology, firms trade emissions permits at a uniform price for each time period that is independent. No permit banking is allowed.

A slope-taking equilibrium of the emissions trading market is defined as a triple of the permit price, net sales of permits, and price impacts such that (i) total net sales of permits must equal zero; (ii) each firm maximizes its profits, given the assumed price impacts; and (iii) the assumed price impacts coincide with the true price impacts (Weretka, 2011a). Market clearing and optimization are also assumed in models of perfect competition and imperfect competition. What makes a model of a slope-taking equilibrium different from these models is that all firms affect the permit price by changing their net sales of permits. When one firm deviates from equilibrium by changing its net sales of permits, other firms respond optimally to this price change by adjusting their net sales of permits. Perfect competition assumes no price impacts. Familiar models of imperfect competition such as Cournot and supply function equilibrium assume that when one strategic firm deviates from equilibrium by changing its net sales of permits, other strategic firms hold net sales of permits constant. In these models, any deviation from equilibrium is absorbed by competitive fringe.

Given the supply response to the market price by other firms, firm i determines its net sales of permits so as to maximize its profit π_i subject to its abatement technology:

$$\underset{q_i}{\text{Max.}}\ \pi_i = pq_i - C_i(e_{0i} - q_i), \qquad i = 1,\dots, N, \tag{1}$$

where C_i is the cost function of abatement of firm i, and e_{0i} is firm i's initial endowment of emissions of the pollutant subject to regulation. Firm i's emissions of the pollutant, e_i, are given by $e_{0i} - q_i$. Each firm trades q_i, which becomes positive for net suppliers and negative for net buyers in the emissions trading market. Because our focus is on bilateral oligopoly, the number of firms, denoted by N, is assumed to exceed two for the rest of the paper.

The first-order condition for firm i's profit maximization in (1) is

$$-\theta_i\, q_i + [p - (-C_i')] = 0, \qquad i = 1,\dots, N, \tag{2}$$

where $\theta_i \equiv -\partial p/\partial q_i$ denotes firm i's price impact, i.e., its ability to affect the permit price by changing its net sales of permits, and $-C_i'$ denotes firm i's marginal abatement cost. The second term on the left-hand side in (2) indicates markup, which can be written as $\theta_i\, q_i$. The larger θ_i becomes, the more market power firm i exerts. Note that in the case of competitive equilibrium, each firm has no price impact. Thus, θ_i becomes zero for any firm and the permit price is equal to the marginal abatement cost at competitive equilibrium. Assuming that firm i's cost function of abatement is quadratic of the form $C_i = C_0 - \alpha_i e_i + 0.5\beta_i e_i^2$, and that $C_0 > 0$, $\alpha_i > 0$, and $\beta_i > 0$, the marginal abatement cost is given by $\alpha_i - \beta_i(e_{0i} - q_i)$, and (2) leads to the optimal net sales, q_i^S, in a slope-taking equilibrium:

$$q_i^S = m_i(p - \alpha_i + \beta_i e_{0i})/(1 + m_i\beta_i)\,, \qquad i = 1,\dots, N. \tag{3}$$

where $m_i \equiv 1/\theta_i$.

In a slope-taking equilibrium model, firm i is assumed to change its net sales of permits by a sufficiently small amount, denoted by ε_i, so that it can obtain a good estimate of the price impact of firm j, denoted by θ'_j, $j \neq i$. The small change in net sales makes the permit price diverge from the equilibrium level, and each firm adjusts its net sales in response to this out-of-equilibrium price. This change in the permit price defines the inverse demand function for firm i, whose slope is given by θ'_i. As a result of these responses, the market becomes clear and the permit price moves back to the equilibrium level. Specifically, an off-equilibrium market clearing condition can be written as

$$q_i + \varepsilon_i + \sum_{j \neq i} Q_j(p) = 0\,, \qquad i = 1,\dots, N, \tag{4}$$

where Q_j denotes the supply function of firm j. Because of the assumption of a quadratic cost function, firms' supply functions become linear in the permit price and the slopes of firms' supply functions are constant for any level of the price. Totally differentiating (4) yields the estimate of m_i, which corresponds to the *assumed* price impact and is denoted by m'_i:

$$m'_i = \sum_{j \neq i} \partial Q_j(p)/\partial p\,, \qquad i = 1,\dots, N. \tag{5}$$

The slope of firm i's supply function, which corresponds to the *true* price impact, is obtained by differentiating (3) with respect to the permit price:

$$\partial Q_i(p)/\partial p = m_i/(1 + m_i\beta_i)\,, \qquad i = 1,\dots, N. \tag{6}$$

By assumption, the assumed price impact in (5) coincides with the true price impact in a slope-taking equilibrium. Thus, $m'_i = m_i$, and from (5)

$$\sum_{j=1}^{N} m_j = (N-1)\sum_{j=1}^{N} \partial Q_j(p)/\partial p = (N-1)\Big[\,\partial Q_i(p)/\partial p + \sum_{j \neq i} \partial Q_j(p)/\partial p\Big]$$

$$= (N-1)[\partial Q_i(p)/\partial p + m_i]. \qquad (7)$$

Substituting (6) into (7) yields

$$m_i + [m_i/(1 + m_i\beta_i)] = \sum_{j=1}^{N} m_j/(N-1), \qquad i = 1,\dots, N, \qquad (8)$$

and the solution in (8) leads to firm *i*'s price impact θ_i. Equation (8) implies that the smaller β_i, the larger θ_i. Thus, price impacts of firms depend on the convexity of firms' cost functions.

Note that firm *i*'s price impact can be written as the ratio of a harmonic mean of $(\theta_j + \beta_j)$ over all but firm *i* to $(N-1)$. To see this, first aggregate all terms in (8):

$$\sum_{j=1}^{N} \{1/[(1/m_j) + \beta_j]\} = \sum_{j=1}^{N} m_j/(N-1). \qquad (9)$$

Then, from (8) and (9),

$$m_i = \sum_{j\neq i} \{1/[(1/m_j) + \beta_j]\} = \sum_{j\neq i} [1/(\theta_j + \beta_j)]\,. \qquad (10)$$

Since $m_i = 1/\theta_i$ by definition, (10) can be rewritten as

$$\theta_i = 1/\{\sum_{j\neq i} [1/(\theta_j + \beta_j)]\} = H(\theta_j + \beta_j \,|\, j \neq i)/(N-1)\,, \qquad (11)$$

where $H(\cdot)$ denotes a harmonic mean.

The equilibrium price of permits, p^S, is obtained by solving the condition for market clearing:

$$p^S = \sum_{j=1}^{N} M_j(\alpha_j - \beta_j e_{0j}) / \sum_{j=1}^{N} M_j, \qquad (12)$$

where $M_i \equiv m_i/(1 + m_i\beta_i)$. Given the retail price and quantity, a slope-taking equilibrium of the emissions trading market is now defined by p^S, the net sales vector $(q_1^S,\dots, q_N^S)$, and the price impact vector $(\theta_1,\dots, \theta_N)$. Note that in case of competitive equilibrium, $M_i = 1/\beta_i$, and the equilibrium permit price, p^*, becomes

$$p^* = \sum_{j=1}^{N} [(\alpha_j/\beta_j) - e_{0j}] / \sum_{j=1}^{N} (1/\beta_j). \qquad (13)$$

If all trades share the identical slope of the marginal abatement cost function, β, the permit price at a slope-taking equilibrium becomes equal to that at competitive equilibrium. In this case, from (8), $m_i = (N-2)/\beta$ and

$$p^S = \sum_{j=1}^{N} [(\alpha_j - \beta e_{0j}] / N. \qquad (14)$$

Then, from (13) and (14), $p^S = p^*$ if the slope of the marginal abatement cost function is β for all traders. .

2.2. Hypothesis

The model presented above raises a couple of important research questions we address with laboratory experiments. First, as (8) indicates, price impacts depend on the curvature of the marginal abatement cost function: the smaller β_i is, the larger the price impact of firm *i*. Thus, given the initial endowment of emission allowances and the distribution of α_i, if β_i of each net seller of permits is smaller than that of each net buyer, the market power on the sellers' side exceeds that on the buyers' side. To see this, suppose that *n* identical sellers and *n* identical buyers trade emissions permits. Thus, $\alpha_i = \alpha_j = \alpha_s$ and $\beta_i = \beta_j = \beta_s$ for all sellers, and $\alpha_i = \alpha_j = \alpha_b$ and $\beta_i = \beta_j = \beta_b$ for all buyers. Then, the absolute value of the net sales of permits becomes identical across all traders, and the difference in the absolute value of the markup depends only on the price impact. The following hypothesis summarizes the effect of the slope of the marginal abatement cost function on the markup.

Hypothesis 1. In the case of *n* identical sellers and *n* identical buyers trading emissions permits,

$$\beta_s \overset{>}{\underset{<}{-}} \beta_b \Leftrightarrow \left| p - (-C') \right|_{i \in S} \overset{<}{\underset{>}{-}} \left| p - (-C') \right|_{j \in B}, \qquad i,j = 1,\ldots,n.$$

where *S* and *B* denote sets of sellers and buyers, respectively.

Second, the effects of the initial endowment of emissions allowances also depend on the curvature of the marginal abatement cost function. From (12), in the case of *n* identical sellers and *n* identical buyers trading emissions permits, the permit price at a slope-taking equilibrium can be written as

$$p^S = [(M_s\alpha_s + M_b\alpha_b) - (\beta_s M_s e_{0s} + \beta_b M_b e_{0b})] / (M_s + M_b), \qquad (15)$$

where $e_{0i} = e_{0s}$, for $i \in S$ and $e_{0i} = e_{0b}$, for $i \in B$. Given the total allowance of emissions, the effect of initial endowments for buyers on the equilibrium price of permits is given by

$$\frac{\partial p^s}{\partial e_{0b}} = \frac{\beta_s M_s - \beta_b M_b}{M_s + M_b} \qquad (16)$$

Equation (16) implies the following hypothesis on the effects of initial allocation of emissions permits:

Hypothesis 2. In the case of *n* identical sellers and *n* identical buyers trading emissions permits,

$$\beta_s \underset{<}{\overset{>}{-}} \beta_b \Leftrightarrow \frac{\partial p^s}{\partial e_{0b}} \underset{<}{\overset{>}{-}} 0,\ \frac{\partial p^s}{\partial e_{0s}} \underset{>}{\overset{<}{-}} 0 .$$

Finally, as (13) and (14) imply, if all trades share the identical slope of the marginal abatement cost function, the permit price at a slope-taking equilibrium becomes equal to that at competitive equilibrium. This holds for any feasible allocation of permits prior to trading, and is summarized by the following hypothesis:

Hypothesis 3. The price of permits at a slope-taking equilibrium coincides with that at competitive equilibrium if all trades share the identical slope of the marginal abatement cost function.

3. LABORATORY IMPLEMENTATION

3.1. Experimental Design

We conducted a computerized laboratory experiment at Tohoku University on March 10, 2011, using a so-called ‘z-tree’ program (Fischbacher, 1999). The experiment included four sessions and each session lasted for approximately 90 minutes. Sixteen subjects were randomly assigned to each session. In each session, four subjects traded emissions permits in a computerized single unit double auction. The number of trading periods was ten and this number of trading periods had not been disclosed to the subjects until the end of the session. Most of the subjects were either undergraduate students or vocational school students. Subjects did not know who had joined the session. Each subject participated in one of the four sessions and received an average of US$30 (1 US dollar = 80 yen) as a reward, which depended on how much the subject earned by trading permits in the experiment. Prior to each session, we explained details of the trading rules to the subjects, and the subjects were asked to read the trading instructions carefully. In describing the trading rules of the experiment, we avoided using terminology that suggested emissions trading. In each session, we made subjects understand the rules of trading completely through practice before the experiment started.

Table 1 summarizes the experimental design. Holding total emissions (40) constant, we assumed three treatments that differed in the initial endowment of emissions permits and the marginal abatement cost functions. We conducted two sessions for each treatment. Each subject faced a marginal abatement cost function, $-C' = \alpha_i - \beta_i(e_{0i} - q_i)$. For each treatment, we assumed marginal abatement cost functions and initial allocation of emissions permits so that subjects A and B would be buyers and subjects C and D would be sellers. To see the effect of the convexity of the marginal abatement cost function on market power, the parameter β for subjects A and B was assumed to be smaller than that for subjects C and D in Treatments 1 and 2. As indicated by Hypothesis 1, the buyers’ market power is expected to exceed that of sellers in these treatments, given the initial allocation of emissions permits. In Treatment 3, all subjects had the identical value of β. Given the initial allocation of emissions permits, this implies that market power is expected to be identical across all subjects, as indicated by Hypothesis 3. To see the effect of the initial allocation of emissions permits on market power, the initial allocation of emissions permits differed across subjects in Treatment 2 while the same amount of permits was initially assigned to each subject in Treatments 1 and 3.

Table 1. Experimental setting

		Subject A	Subject B	Subject C	Subject D
Treatment 1	β	1	1	5	5
	a	150	150	150	150
	Initial endowment	10	10	10	10
Treatment 2	β	1	1	5	5
	a	150	150	130	130
	Initial endowment	6	6	14	14
Treatment 3	β	1	1	1	1
	a	150	150	130	130
	Initial endowment	10	10	10	10

Table 2 summarizes the benchmark for slope-taking equilibrium for each treatment, which is computed as a solution of the equilibrium price, the net trade vector, and the price impact vector in section 2.1. Since the market power of buyers is assumed to exceed that of sellers in Treatments 1 and 2, the price of permits under the slope-taking equilibrium is lower than that under perfect competition, and profits of buyers (sellers) under the slope-taking equilibrium are larger (smaller) than those under perfect competition in the benchmark of these treatments. To see the loss in allocative efficiency due to market power, we compute an efficiency measure of the slope-taking equilibrium relative to the competitive equilibrium, which is defined as the ratio of an increase in aggregate profits due to emissions trading under the slope-taking equilibrium to that under the competitive equilibrium (Ledyard and Szakaly-Moore, 1994). In all treatments, the market power of bilateral oligopoly would reduce efficiency by approximately 10%, as indicated by 'SE efficiency', which denotes an efficiency measure of the slope-taking equilibrium relative to the competitive equilibrium. For each treatment, the benchmark of perfect competition indicates that the equilibrium price of emissions permits would be 130 and that the competitive distribution of emissions would place 20 with subjects A and B and 0 with subjects C and D.

Table 2. Benchmark for slope-taking equilibrium for each treatment

	Treatment 1		Treatment 2		Treatment 3	
	Buyer	Seller	Buyer	Seller	Buyer	Seller
Profits under No trade	-1980	-600	-2546	-330	-1980	-1680
Profits under CE	-1935	-325	-2455	195	-1935	-1625
Profits under SE	-1891	-402	-2367	51.4	-1941	-1635
SE efficiency (%)	89.7		90.9		87.3	
CE price	130		130		130	
SE price	123.3		120.6		130	

Note: CE denotes the competitive equilibrium benchmark, SE denotes the slope-taking equilibrium benchmark, and SE efficiency denotes an efficiency measure of the slope-taking equilibrium relative to the competitive equilibrium, which is defined as the ratio of an increase in aggregate profits due to emissions trading under the slope-taking equilibrium to that under the competitive equilibrium.

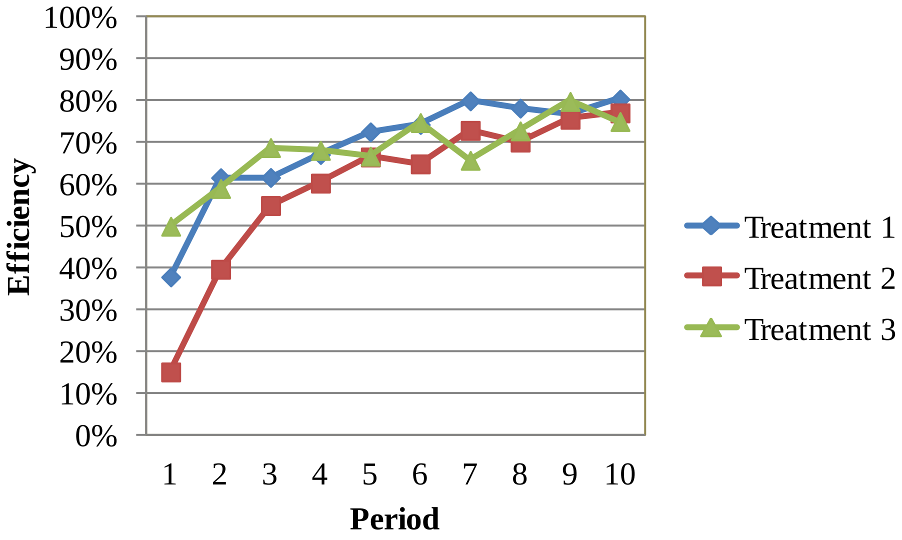

Figure 1. SE efficiency in each period

3.2. Results

First, we compare allocative efficiency among three treatments. Figure 1 shows SE efficiency in each period. Allocative efficiency increased as the trading period proceeded in all treatments. Table 3 compares the average allocative efficiency across three treatments. There seems to be some difference in SE efficiency across treatments. In fact, as shown by Table 4, a Mann−Whitney test with the null hypothesis that probability distributions of SE efficiency are identical across all treatments indicates that the difference between Treatments 1 and 2 was statistically significant. It also implies a statistically significant difference in SE efficiency between Treatments 2 and 3.

Table 3. Average allocative efficiency of each treatment

	Treatment 1	Treatment 2	Treatment 3
Period 1 to 5	0.601	0.473	0.625
Period 6 to 10	0.780	0.721	0.737
All periods	0.691	0.597	0.681

Table 4. Result of a Mann−Whitney test

SE efficiency	All periods	Period 1 to 5	Period 6 to 10
Treatment 1 vs Treatment 2	1.884*	1.925*	1.270
Treatment 1 vs Treatment 3	0.128	-0.375	0.525
Treatment 2 vs Treatment 3	-1.863*	-2.252**	0.430
Price of permits	All periods	Period 1 to 5	Period 6 to 10
Treatment 1 vs Treatment 2	2.786***	3.633***	4.471***
Treatment 1 vs Treatment 3	-4.258***	-3.671***	-5.479***
Treatment 2 vs Treatment 3	-6.909***	-6.505***	-9.451***

Note: * indicates significant at 10% level, ** indicates significant at 5% level, and *** indicates significant at 1% level.

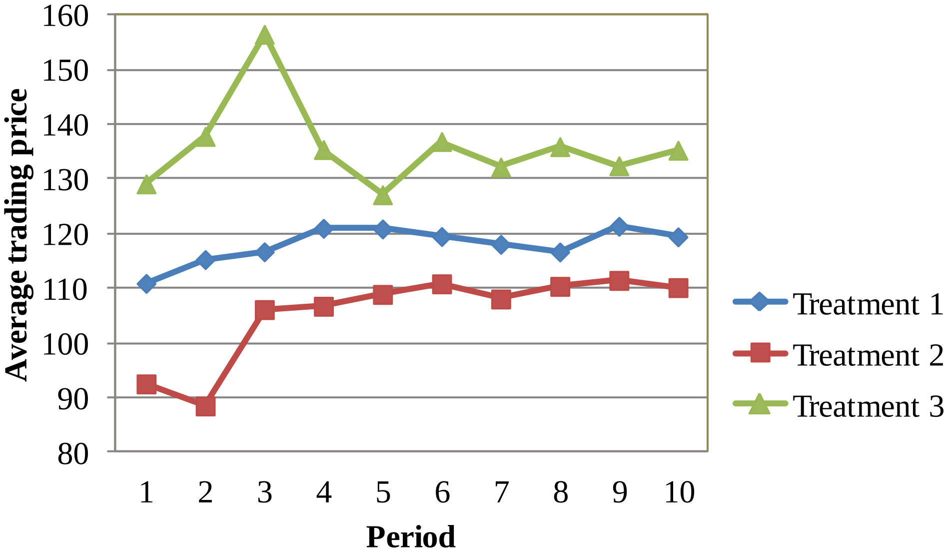

Figure 2. Average permit price in each period

Second, we compare the price of emissions permits among three treatments. Figure 2 shows the permit price in each period while Table 5 summarizes the average price of permits in each treatment. It seems that the permit price in each treatment became closer to that of the benchmark for the slope-taking equilibrium as permit trade proceeded. As indicated by Hypothesis 1, if the slope of the marginal abatement cost function of buyers is smaller than that of sellers (i.e., $\beta_b < \beta_s$), like Treatments 1 and 2 in this experiment, the buyers' market power exceeds that of sellers. This claim is supported by the observed prices of permits in both Treatments 1 and 2, which were persistently lower than the competitive price during all periods of the experiment. Also, as implied by Hypothesis 3, the observed price of permits in Treatment 3 where all subjects have the same β was close to that of the competitive benchmark in most of the trading periods. Moreover, as Hypothesis 2 indicates, the price of permits in Treatment 2 was persistently lower than that in Treatment 1 during all periods of the experiment. In the case that the market power of buyers exceeds that of sellers ($\beta_b < \beta_s$), like Treatments 1 and 2 in this experiment, an increase in sellers' initial endowment of emissions permits enhances buyers' market power, thereby reducing the price of permits. Indeed, the Mann−Whitney test shown in Table 4 supports these findings.

Table 5. Average trading price of each treatment

	Treatment 1	Treatment 2	Treatment 3
Period 1 to 5	117.0	100.6	137.2
Period 6 to 10	119.0	110.2	134.6
All periods	118.0	105.4	135.9

Finally, we analyze the effectiveness of the market power of each subject. Subjects with market power could increase their total profit in bilateral oligopoly. To analyze market power effectiveness, we calculate the index, denoted M, which is defined as the ratio of the realized supracompetitive total profit of the strong market side to its supracompetitive total profit in the market power benchmark (Sturm, 2008). Specifically, $M = (\pi - \pi^{CE})/(\pi^{SE} - \pi^{CE})$, where π is the realized total profit of the market power subjects, π^{CE} is their total profit under the competitive benchmark, and π^{SE} is their total profit under the slope-taking equilibrium benchmark. Note that M is 1 if the realized profit of the market power subjects is equal to their total profit under the slope-taking equilibrium benchmark ($\pi = \pi^{SE}$), but it may exceed 1 for the case of successful price discrimination or it may be below 1 if the realized total profit of the market power subjects is less than their total profit under the benchmark.

Figure 3 shows the index of market power effectiveness in Treatments 1 and 2. Since Hypothesis 1 implies that market power of buyers (subjects A and B) exceeds that of sellers (subjects C and D) in these treatments, the market power subjects are subjects A and B, and their total profit was used to compute M. For Treatment 3, the index of market power effectiveness was not computed because no subject was considered to be the 'strong market side.' In Figure 3, both Treatments 1 and 2 exhibited M that exceeded 1: on average, M was approximately 1.3 in Treatment 1 and 1.7 in Treatment 2. Thus, buyers exerted market power to increase their profit in these treatments. Turning to how M changed along with trading, buyers effectively exerted market power until the seventh period in both treatments. For the last three periods, however, their market power decreased and M converged to 1 in Treatment 1, while their market power was enhanced in Treatment 2.

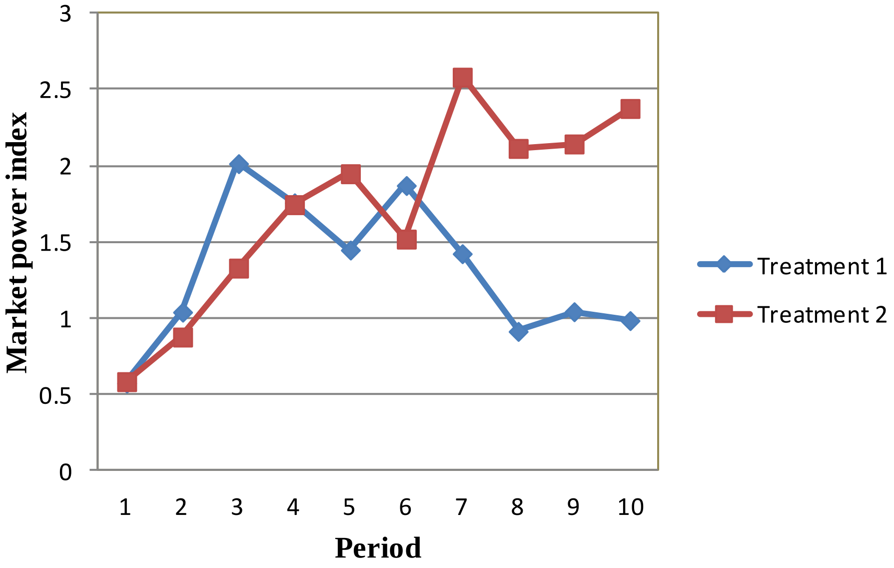

Figure 3. Index of market power effectiveness in each period

4. CONCLUSION

Our results suggest that a slope-taking equilibrium model of bilateral oligopoly could better describe market outcomes of emissions trading. As the model predicts, how market power is exerted depends on both the curvature of the marginal abatement cost function and the initial endowment of emissions permits. If the marginal abatement cost function of buyers is less steep than that of sellers, the price of permits became lower than that under perfect competition. This is because the market power of buyers exceeds that of sellers. The price of permits was close to that under perfect competition when all traders have the same slope of the marginal abatement cost function. In both cases, some portion of allocative efficiency achieved by emissions trading was lost because of imperfect competition. In the case that the market power of buyers exceeds that of sellers, an increase in sellers' initial endowment of emissions permits enhances buyers' market power, thereby reducing the permits price.

Persistent divergence in the equilibrium price of emissions permits from the competitive level, which occurs because of the difference in the curvature of the marginal abatement cost function and the initial endowment of emissions permits, is in line with the literature on laboratory experiments of emissions trading (Sturm, 2008).

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